The application of Kelp (*Laminaria digitata*) in marginal agroecosystems

by

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Abstract

Lazybeds were a historic agricultural system that used a ridge and furrow approach to improve soils for crop production in marginal land. These Lazybed systems were further characterised by the use of dung/manure and marine macroalgae (in coastal areas) as fertilisers. This thesis aimed to investigate whether Lazybeds could be sustainably re-cultivated and how the use of kelp (*Laminaria digitata*) and dung/manure fertilisers in the system affect food production. It was important to determine how kelp performed in comparison to more conventionally used organic fertilisers such as animal dung/manures. Further, knowledge gaps existed in understanding how earthworm populations, key to processing nutrients and incorporation of organic matter, would interact with kelp as a food source. To better understand fertiliser and management regimes, climatic variables and earthworm communities, their effects on changes in physico-chemical and biological soil properties and crop yields need to be disentangled. This research primarily investigated how the use of kelp fertilisers on marginal soils could support plant growth, using a combination of laboratory, glasshouse, and field studies. Results show that the effects of organic fertiliser type on crop yields was significant, with fresh kelp increasing yields for some crops when compared to animal manures and commercially available seaweed extract liquid fertiliser. However, changes in soil properties, conventionally associated with improved crop performance, were often found to be similar for both kelp and animal manure-fertilised treatments. Further experimentation found that fresh kelp consistently outperformed kelp at various decompositional stages. This suggests that the mechanism leading to increased crop production in fresh kelp fertilised treatments is rapidly degraded during the decomposition process. Further, kelp fertilisers were found to modify crop growth response to reduced watering, enhancing crop production and increasing resistance to drought more than manure fertilisers. In addition, experiments presented in this thesis found that earthworms decreased the efficacy of kelp fertilisers. This suggests that the mechanisms driving increases in plant growth are partly degraded when kelp is consumed and egested by earthworms. Additional research is required in field settings to evaluate how earthworms selectively feed, and if kelp is avoided, then the crop may benefit from other earthworm activity. Furthermore, kelp and manure-based fertilisers were comparable in their ability to increase yields from continuous to alternate cropping (rotations with rest periods) systems, although yields were greater in the kelp-fertilised, alternate cropping treatment. Determination of Lazybed effects on soil properties and elucidating the mechanisms driving increases in plant growth, could be used to determine land management strategies to enhance sustainable food production, bringing areas of marginal land back into production. However, kelp is a limited natural resource which is already threatened by multiple climatic and anthropogenic pressures and its presence is geographically and temporally variable. As such, there is very limited scope for these agricultural systems to be adopted at scale. However, aspects of the Lazybed system may be most valuable in small-scale coastal systems where economic constraints and environmental concerns make the use of inorganic fertilisers less feasible.

Table of Contents

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List of Figures

List of Tables

1. General Introduction

1.1 High Level Summary

Lazybeds are a historic agricultural system that used a ridge and furrow approach to improve soils for crop production on marginal land. These Lazybed systems were further characterised by the use of dung/manure and marine macroalgae (in coastal areas) as fertilisers and offer scope to be recultivated in the modern era. This chapter outlines the primary research drivers and gaps addressed in this thesis, along with the overarching aim and objectives.

1.1.1 Sustainability in Agriculture

For agricultural systems to be sustainable they must meet the needs of the present without compromising the ability of future generations to meet their needs (Altieri et al., 2015; Clunes et al., 2022) (see Section 2.1 for further details). Since the latter half of the 20th century, soil degradation has intensified and globally 33% of soils are degraded and by 2050 this figure could reach 90% (FAO & ITPS, 2015; IPBES, 2018). However, many global agricultural systems were once sustainable, although admittedly under much lower pressure from a smaller human population (Kopittke et al., 2019). These sustainable agroecosystems recognised the importance of working within the natural production limits of the system, only obtaining nutrient inputs from sources within the biosphere such as manure and compost and developed crop rotation systems to help stabilise the soil (Brunt, 2002). To understand the implications of these practices on the sustainability of agriculture, it is essential to consider the global nutrient cycle.

1.1.2 Global nutrient cycle

The global nutrient cycle embodies the storage and movement of nutrients between the oceans, atmosphere, and terrestrial biosphere (Costanza et al., 1998; Porazinska D L., 2013). Nutrient cycling is fundamental to the Earth's primary production system, facilitating the capture and transfer of energy to higher trophic levels (Finzi et al., 2011). Through the dependency of almost all known life on photosynthetically derived carbon, the global nutrient cycle drives the Earth's biological systems (Gruber & Galloway, 2008). However, the anthropogenic exploitation of biological systems for production of food and fibre has perturbed global nutrient cycling (Power, 2010). The manufacture and use of inorganic fertilisers has led to an imbalance of nutrient inputs, mainly nitrogen (N) and phosphorus (P) in the biosphere, degrading ecosystem processes and environmental quality (Galloway et al., 2008; Jones et al., 2013). The effects of disrupted nutrient cycles are especially evident in agroecosystems, which provide crucial ecosystem services but are often compromised by intensive agricultural practices.

1.1.3 Agroecosystems and Ecosystem Services

Agroecosystems can deliver multiple ecosystem services, whilst retaining their primary function in the provision of food (Liu et al., 2022) (see Section 2.2 for further details). Further, the importance of other ecosystem services which agroecosystems rely on and have synergies with e.g. pollination, pest control and nutrient cycling, are increasingly recognised (Power, 2010). However, some agricultural practices negatively impact ecosystem service provision and can result in losses to said ecosystem services e.g., biodiversity, soil, and carbon stores (Liu et al., 2022). This has historically been viewed as a trade-off, a result which is the inevitable consequence of producing enough food to support a growing world population (Power, 2010). However, currently many farmers are starting to recognise the importance and value of ecosystem services to support their goals of food production, representing a change in thinking where food production requires a healthy, high functioning environment (Norton et al., 2022). This work, will in part, seek to assess if environmental degradation may be reduced in food production systems, through investigation of aspects of a historic potentially lower impact agroecosystem, namely Lazybeds and how these can be used, or aspects incorporated into modern systems.

1.1.4 Historic Practices: Lazybed Systems

In areas with marginal soils, land management techniques, e.g., the Lazybed system, modified the soil structure (Darling, 1945). Lazybeds are a type of ridge and furrow agricultural system, which historically was commonly practiced by Scottish island communities and subsistence farmers, however examples can be found across Britain and Ireland (Foster & Smout, 1994). Lazybeds consist of parallel banks and ridges dug by hand generally on marginal soils with the aim of improving conditions for crop growth (Nature Scot, 2019). These systems often used locally sourced marine macroalgae and animal manures to support nutrient levels in the soils (Darling, 1945; Entwistle et al., 2000) (see further details in Section 2.3). This thesis will refer to Lazybed systems which encompasses the physical structures but also associated management practices e.g., macroalgae fertilisation in coastal areas. Ridge and furrow farming systems have persisted for millennia as a land management strategy (Fowler, 2002) and can be seen in many forms, including modern potato production systems; however, these contrast starkly to the historic Lazybed systems.

1.1.5 Comparing Historic and Modern Agricultural Systems

Although modern ridge and furrow potato production systems are high yielding, there are growing concerns behind the environmental impact of these systems. It is thus important to investigate whether historic ridge and furrow techniques such as the aforementioned Lazybed system were as susceptible to soil degradation, or whether the practices were more sustainable (Butt & Nuutinen, 2021). If they are found to be more sustainable, aspects could be taken from the historic system and incorporated in the development of modern agricultural systems (Butt & Nuutinen, 2021). For example, does the use of kelp, increase the sustainability of the system, as was observed in systems using more conventional inputs such as manure by Blair et al., (2006)? Furthermore, this thesis will assess whether historic abandoned ridge and furrow systems could be successfully recultivated, providing opportunities for small scale food production systems on marginal land, which has been achieved in other remote and/island communities across the world (Georgeou et al., 2022) and with similar aims listed in the United Nations Sustainable Development Goals (Viana et al., 2022) (see Section 2.4 for further discussion).

1.1.6 Soil Nutrient Management

In the terrestrial biosphere, soils are the main store of N and P, and the functions of healthy soils facilitate the transfer of nutrients to vegetation (Kopittke et al., 2023). However, the perturbation of nutrient cycles and the subsequent loading of these nutrients in agricultural systems, has degraded soil functions (Costantini et al., 2018). The degradation of soils, which are the foundation of most agricultural practices, seriously threatens the ability of these systems to produce food sustainably (Kraamwinkel et al., 2021). The importance of soil health is gaining recognition to farmers, policy makers and wider society, as the impacts of soil degradation are felt (Handayani & Hale, 2022; Harris et al., 2022). A healthy soil has a good combination of structure, chemistry, organic matter, biology, and water permeability dependent on soil type/classification, all of which promote ecosystem functions such as food production, clean water, and climate mitigation (Bedigian, 2005). For an agricultural system to be sustainable it is therefore essential that management practices must not degrade the condition of the soil and its ability to support plant growth, but also must ensure that actions do not result in wider negative environmental impacts (Harris et al., 2022).

1.1.7 Organic Fertilisers: Manure and Marine Macroalgae

A wide variety of organic fertilisers have been used to increase yields in agricultural systems for millennia (Bogaard et al., 2013). Fertiliser application to land is an important management strategy in agricultural systems where natural nutrient cycles are perturbed, leading to the removal of nutrients from a system over time, which can result in diminishing crop yields if actions are not taken to restore those nutrients (Kidd et al., 2017). The use of animal manure as a fertiliser to replace nutrients removed from agricultural systems is widespread (Blair et al., 2006), however, the use of marine macroalgae has historically been confined to coastal regions, where the resource was readily available (Entwistle et al., 2000). The benefits of macroalgae on plant growth are documented in historical accounts of life in coastal communities in north western Europe (Darling, 1945; Dodgshon, 1993), however scientific investigation into the use of marine macroalgae as a fertiliser resource is extremely limited (Knox et al., 2015). Marine macroalgae are however commonly used in the production of commercially available fertilisers which extract and/or isolate compounds known to have beneficial effects on plant growth (González et al., 2013). Literature on the efficacy of these extracts is quite comprehensive, however, fresh marine macroalgae are known to contain biostimulants which are rapidly degraded and subsequently not present in as high concentrations in extracts as in their primary form, however direct studies of the use of fresh algae are extremely limited (Popescu, 2013). Moreover, nutrients are lost in the processing of marine macro algae to produce these extracts, which could be of further benefit to plant growth. However, composting processes often used in the production of marine macro algae extracts and the treatment of animal manures has advantages such as a reduced volume and mass (thereby making application to land more efficient), and biosecurity benefits through reduced pathogenic risk (Ahmed & Al-Mutairi, 2022; Petersen et al., 2007). Marine algae extracts are classified as biostimulants, rather than fertilisers, as the primary responses observed in plants are internal mechanistic processes (Ali et al., 2021). Marine algae as a raw fertiliser and extracts from marine algae, are considered to have a lower environmental impact than inorganic NPK fertilisers (Ali et al., 2021). Inorganic fertilisers require an energy and resource intensive production process and are as a consequence increasingly on the agenda as the agricultural industry looks for fertilisers options to increase the sustainability of its practices, whilst feeding a growing population (Ali et al., 2021; Renaut et al., 2019). Further, a growing body of evidence suggests that organic fertilisers, such as manure, act as better long-term fertilisers for increasing crop yields than inorganic fertilisers by improving multiple soil parameters to support plant functioning and therefore yields (Cai et al., 2019). This thesis will investigate whether, kelp is comparable in its effects on plant growth to manure and seaweed extracts, however, no comparisons to industrial NPK are made as it was deemed inappropriate to introduce these (for experimental purposes) to the selected field experiments which are located in a protected site, and glasshouse experiments aimed to further investigate the observations made during the field experiments. This thesis, in part, seeks to assess whether additional benefits could be realised from utilising marine macroalgae in its primary form over extracts, acting as both a biostimulant and fertiliser, whilst comparing it against traditionally used manure fertilisers (which are not considered to be biostimulants).

1.1.8 Environmental Impact Considerations and Limitations

A particular focus of this Thesis is given to sites of abandoned Lazybeds on the Isle of Rum (see section 2.2.1 for more detail) which have not returned to their pre agricultural state due to continued grazing pressures (SNH, 2018). Grazing pressures in many areas on Rum where Lazybeds have been historically cultivated, can be characterised as high due to the ungulate populations present, although management strategies are being trialled so these populations can be sustainably managed with the hope that natural ecosystems can regenerate (Vuorinen et al., 2020).

As with any proposed changes to current land use, robust environmental impact assessments should be conducted which identify unintended consequences associated with the new management strategy (Suckling et al., 2021). For example, flora, fauna and fungal assemblages on the areas of Lazybeds to be recultivated need to be assessed (Belmont et al., 2022). This will help identify any sites which contain locally, nationally, or globally rare protected species or habitats, which would not be suitable for recultivation, as the change in land use and management would reduce suitable habitat for these rare species (Burkhart, 2007). Further, turning over the soil in the construction of the Lazybeds potentially would result in the release of carbon stored in the soil: newly developed agricultural practices should recognise the importance of protecting existing soil carbon stores (Dynarski et al., 2020). This would be particularly inappropriate on areas of deep peat soil, which although historically cultivated, their value as globally important carbon stores are being increasingly recognised (Freeman et al., 2022). Further assessments need to be conducted into the use of manures and kelp to maintain appropriate nutrient levels on site and ensure that risks to connected habitats from diffuse agricultural pollution is low (Ayoub, 1999). Moreover, kelp is high in many elements that are not present in as high concentrations in terrestrial systems (Reboredo et al., 2021). Subsequently, it will be important to monitor soils where the kelp is added over time, to ensure that many of the elements do not accumulate to become present in concentrations which have deleterious effects on plant growth (Tye et al., 2000). In addition, the impact of removing kelp from the shoreline needs to be considered (Walton et al., 2022). Shoreline habitats are characterised by dynamic processes, supporting diversity at the terrestrial-marine interface, and play an important role in marine carbon and nutrient cycling (Levin et al., 2001). If Lazybed practices (shoreline kelp harvesting) were to become more widely adopted there is potential that decomposer communities lose their primary food source, with knock on effects for organisms in higher trophic levels, resulting in the collapse of the shoreline food web.

Although it is unlikely that Lazybed systems could be implemented at the necessary scale to resolve issues of global food security, these systems in remote island communities do offer potential to increase food production at local/community scales on marginal land (Georgeou et al., 2022). Parallels can be drawn with other studies which have assessed how small holder farming can support and supplement diets for 80% of Pacific Island populations (Georgeou et al., 2022). Further, it is recognised in UN Sustainable Development Goal 2, that if island communities are increasingly reliant on imports, this represents a loss of food security (Vogliano et al., 2021). However, there is potential that aspects taken from Lazybed systems could be adapted and incorporated into larger scale agricultural systems (Viana et al., 2022). For instance, there is potential for the production process of commercially available fertilisers containing seaweed extracts to be optimised to increase crop yields in industrial scale agricultural systems, however, the viability of this is outside the scope of this thesis.

This thesis aims to assess whether, aspects of historic agroecosystems have a place in the modern food production system and can deliver sustainable food to an ever-growing population, whilst being resilient in the face of climate change.

1.2 Aims and Objectives

The overarching aim of this research programme was to investigate whether abandoned, historic agroecosystems could be sustainably re-utilised and how the use of kelp and dung fertilisers in the systems affects food production. This section sets out specific objectives and how they align with existing scientific knowledge:

(1) Determine whether Lazybed systems affect soil properties and could support food production on marginal land; (Chapter 3)

This objective seeks to determine whether Lazybed systems affect soil properties and can support food production on marginal land. Lazybed farming, a traditional method used in Scotland, involves creating raised beds separated by drainage channels. Modern studies on soil management indicate that such practices can enhance soil aeration, improve drainage, and increase soil fertility.

Current scientific knowledge highlights the importance of soil structure in maintaining agricultural productivity. Research has shown that raised bed systems can mitigate soil compaction, enhance root penetration, and facilitate better water management. These factors are crucial for crop growth on marginal lands, which are often characterised by poor soil quality and drainage issues. By examining Lazybed systems, this research can provide empirical data on their effectiveness in improving soil properties, contributing to the broader field of sustainable agriculture.

(2) Quantify potato production in Lazybed systems; (Chapter 3)

The second objective focuses on quantifying potato production within Lazybed systems. Potatoes are a staple crop in many regions and serve as a critical food source globally. Current agronomic research emphasises the importance of optimised planting techniques and soil management for maximising potato yields.

Studies have shown that raised bed systems can significantly impact potato yields by improving soil temperature, moisture retention, and nutrient availability. These factors are particularly relevant for marginal lands, where conventional farming practices might not yield satisfactory results. By measuring potato production in Lazybed systems, this research can validate the potential of these historic practices in modern agricultural contexts, providing a model for sustainable food production in challenging environments.

(3) Assess how earthworm communities interact with the differing fertiliser types used in Lazybed systems and whether the presence of earthworms impacts the effectiveness of the fertiliser types; (Chapter 5).

The third objective involves assessing how earthworm communities interact with different fertiliser types used in Lazybed systems and whether the presence of earthworms impacts fertiliser effectiveness. Earthworms are known to play a critical role in soil health, contributing to nutrient cycling, soil structure improvement, and organic matter decomposition.

Scientific literature has extensively documented the benefits of earthworms in agroecosystems. Their activity can enhance soil aeration, increase nutrient availability, and improve plant growth. Different fertilisers, such as kelp and manure, can influence earthworm populations and activity. By studying these interactions, this research can shed light on how earthworms contribute to the efficacy of natural fertilisers in Lazybed systems, promoting sustainable fertilisation practices.

(4) Determine how the use of kelp as a fertiliser treatment differs from more conventionally used fertiliser i.e., manure, to affect food production on marginal soils; (Chapter 3, Chapter 4 and Chapter 6).

The fourth objective aims to assess how kelp as a fertiliser treatment differs from conventionally used fertiliser, such as manure, in affecting food production on marginal soils. Kelp, a type of seaweed, has gained attention for its potential as an organic fertiliser due to its high nutrient content and growth-promoting properties.

Recent studies have explored the benefits of kelp in agriculture, highlighting its ability to improve soil health, enhance crop resilience to stress, and increase yields. Kelp contains essential micronutrients, growth hormones, and organic matter that can enrich soil fertility. Comparing kelp to traditional manure, which is also rich in nutrients, can provide insights into their relative effectiveness and suitability for different soil types and crops. This research can contribute to the development of more sustainable fertilisation strategies, particularly for marginal lands where conventional methods may be less effective and economically viable.

Further objectives and hypotheses are presented for each of the experimental chapters.

A combination of field, glasshouse and laboratory experiments have been used to investigate the reinstatement of the given agroecosystem. These experiments were designed to address the aforementioned objectives. This research programme detailed in Section 1.3, builds on current scientific knowledge to investigate the sustainable re-utilisation of historic agroecosystems. By examining Lazybed systems, potato production, earthworm interactions, and the use of kelp versus conventional fertilisers, the research aims to provide actionable insights into sustainable agricultural practices and disentangle the mechanisms driving these processes in agroecosystems.

1.3 Experimental Work to Address Objectives

This thesis has been structured to address the knowledge gaps identified through the literature review (Figure 1). Field experimentation detailed in Chapter 3 has further utilised a dedicated area of previous Lazybed cultivation to work towards meeting objectives 1 and 2. Specifically, this work assessed how kelp (*L. digitata*) and dung fertilisers in Lazybed systems affect crop production and soil properties. It was initially hypothesised that Lazybeds with a mixed kelp+dung fertiliser led to the greatest crop yields through effects on soil properties, due to the co-input delivering multiple and differing benefits to the system from both the kelp and dung. Further work presented in Chapter 3 investigated how the timing and amount of kelp additions affected the growth of a variety of crops and changes in soil properties in controlled glasshouse conditions. Chapter 4 assesses how soil amendments could mediate effects of reduced watering in cropping systems, through changes in soil properties such as soil organic matter content, potentially reducing irrigation requirements. The potential role of earthworms in Lazybed systems and their interactions with kelp fertilisers is detailed in Chapter 5. One of the main insurmountable issues of this study was to assess the sustainability of the multi-year rotation to fallow system traditionally employed for Lazybed cultivations within the time frame of a PhD. This issue was investigated in Chapter 6, through undertaking experiments in controlled (glasshouse) environmental conditions, maintaining growing season conditions which allowed cropping cycles to continue throughout the year. This approach investigated different crop rotation systems and how ecosystem functions are impacted when coupled with the addition of different fertilisers. Finally, Chapter 7 consolidates the findings of the experimental chapters, discussing the implications of these findings in a broader perspective. A general synthesis is given for the experiments in relation to the research question and existing literature in addition to a discussion of the key findings, remaining knowledge gaps and recommended future research directions. Before all of the experimental work a review of relevant literature is provided in Chapter 2.

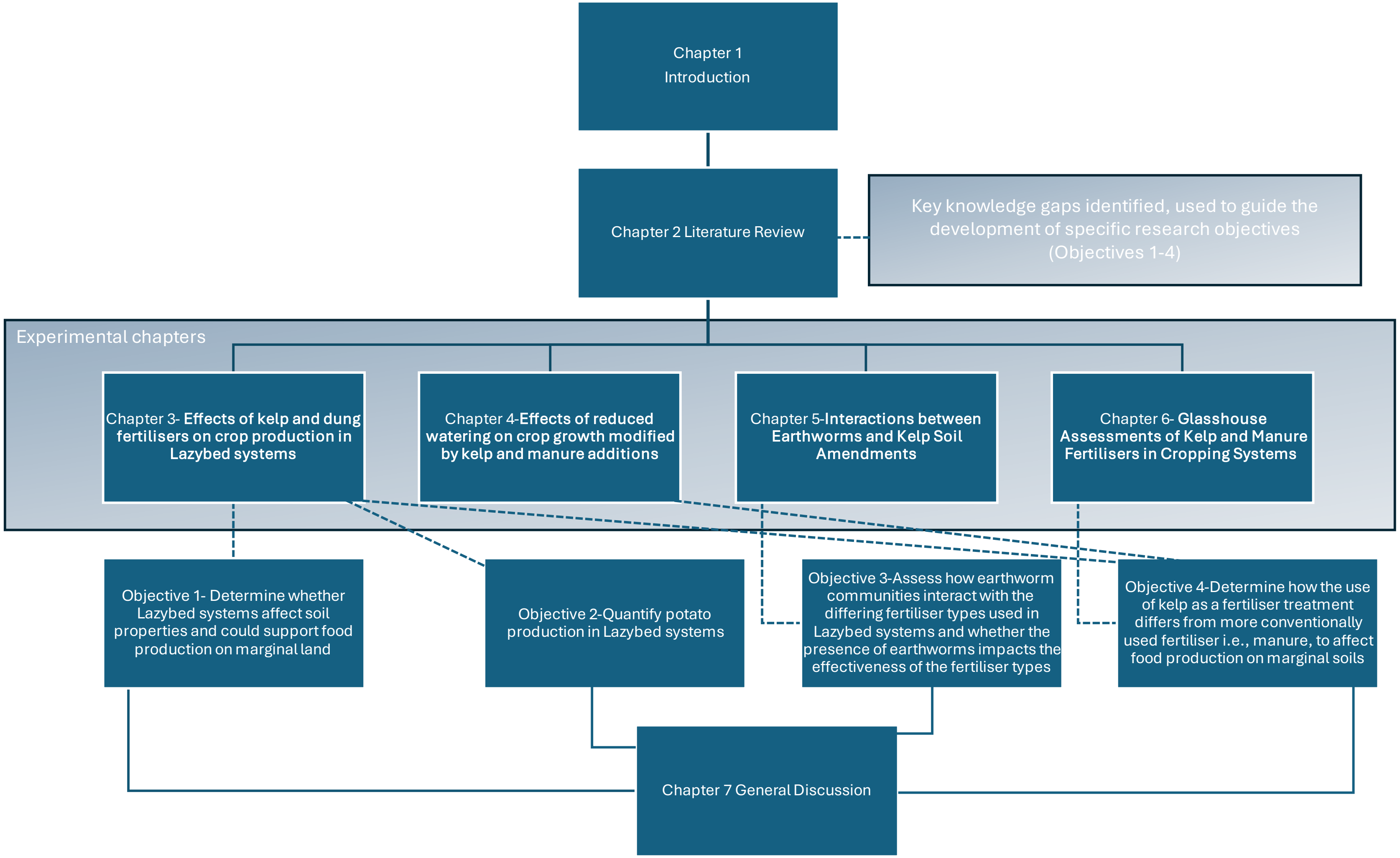

Figure 1 An organogram providing an overview of the thesis structure, lines have been used to indicate flow and the relationship between the research objectives and experimental chapters

2. Literature Review

2.1 Sustainability in Agriculture: Food Security, Population Growth and Climate Change

Food security is perhaps one of the biggest geopolitical and environmental challenges of the 21st century (Keesstra et al., 2016) and is achieved when all people have access to enough safe and nutritious food (Mark, 2012). Currently, 815 million people are defined as food insecure (Westengen & Banik, 2016). With the global population expected to reach 9.8 billion by 2050, and 11.2 billion by 2100, the number of people facing food insecurity is expected to rise by around a third (Tomlinson, 2013). Further, the pressures of climate change may exacerbate the problem of food insecurity (Brown & Funk, 2008). More frequent and severe extreme weather events associated with climate change, such as drought, flooding, heatwaves, and cold spells all have the potential to cause crop failure, reduce yields and cause harvesting problems. As a result of these climate stresses, crops may have increased susceptibility to disease, combined with potential spread of pathogens, into previously uninfected areas which can lead to diminishing crop yields (Elad & Pertot, 2014).

Advances in agriculture in the 20th and 21st century increased food security; however, the sustainability of many of the methods currently employed is unclear and may be leading to reversals in original advances (Jones et al., 2013). The extensive use of inorganic fertilisers, pesticides and heavy machinery has contributed to soil degradation which threatens ecosystem services provided by soils, such as food production (Gregory et al., 2015a). In the EU, 970 million tonnes of soil are lost each year, with losses from arable land equating to over 40% of this (Panagos et al., 2015). In the UK, annual soil degradation costs £1.2 bn, mainly due to losses of organic matter, compaction, and erosion (Graves et al., 2015). The loss of organic matter, which accounts for 47% of the economic losses in agriculture, is attributed to an increased requirement for irrigation, inefficiencies in fertiliser use, and yield reductions due to lower water and nutrient holding capacity of the soils. Further, loss of organic matter from soils has resulted in economic costs through the effects on greenhouse gas (GHG) emissions, flood mitigation and drinking water contamination. Over time, as soils have become degraded, many farms have further tried to intensify their production methods (e.g., using more inorganic fertilisers) to combat decreases in yields, which creates feedback, leading to further soil degradation and decreasing the sustainability of food production (Mulvaney et al., 2009).

Food insecurity has been perceived by many as a problem for developing countries. However, in the UK, 48% of food is imported, this makes the food supply chain susceptible to global and national economic and environmental stressors (Lee and Marsden, 2011). In 2018, two extreme weather events (a very cold and wet winter/spring followed by the longest heatwave in 40 years) gave rise to an average 5% increase in the cost of food with some fruit and vegetables seeing increases of up to 80% (Cebr, 2018). More recently a global financial crisis, a war in Europe and Brexit have fuelled inflation (16.8% in January 2023) leading to food prices rising at their fastest rate in over 40 years (ONS, 2023). Such price rises clearly demonstrate the need for the UK to enhance its food security. There is scope that improvements to food security could, in a small part, at a localised level, be achieved through the small-scale food production on historically cultivated marginal land (Georgeou et al., 2022).

2.1.1 Sustainability in Agriculture; a Scottish Perspective

Agriculture in Scotland is an environmentally, economically and culturally significant industry, however, some aspects of agricultural production can result in negative impacts on ecosystems. An estimated 80% of Scotland's land area is under agricultural production, equating to 5.66 million ha (Scottish Government, 2019). Figure 2 illustrates the extent of livestock farming in Scotland, with only around 10% of land being classified as arable (James Hutton Institute, 2019). The remaining areas are dominated by livestock production and located on land which has poorer soils and unfavourable climatic conditions, which mean the land is classified as unsuitable for commercial arable production. However, historically subsistence levels of crop production occurred in the Highland and Island communities, where pockets of land can be found with greater land capability (Figure 3).

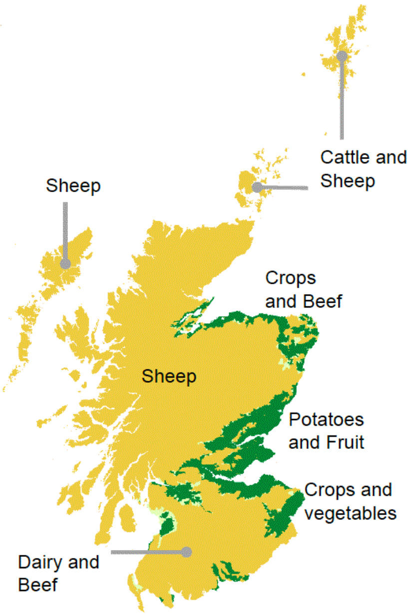

Figure 2 Map of Scotland showing the main farming types in each area. Yellow areas have limited agricultural capacity due to poor soils and topography. Green areas have more favourable soils and can support the production of cereals and vegetables for human consumption (Environment and Forestry Directorate, 2019).

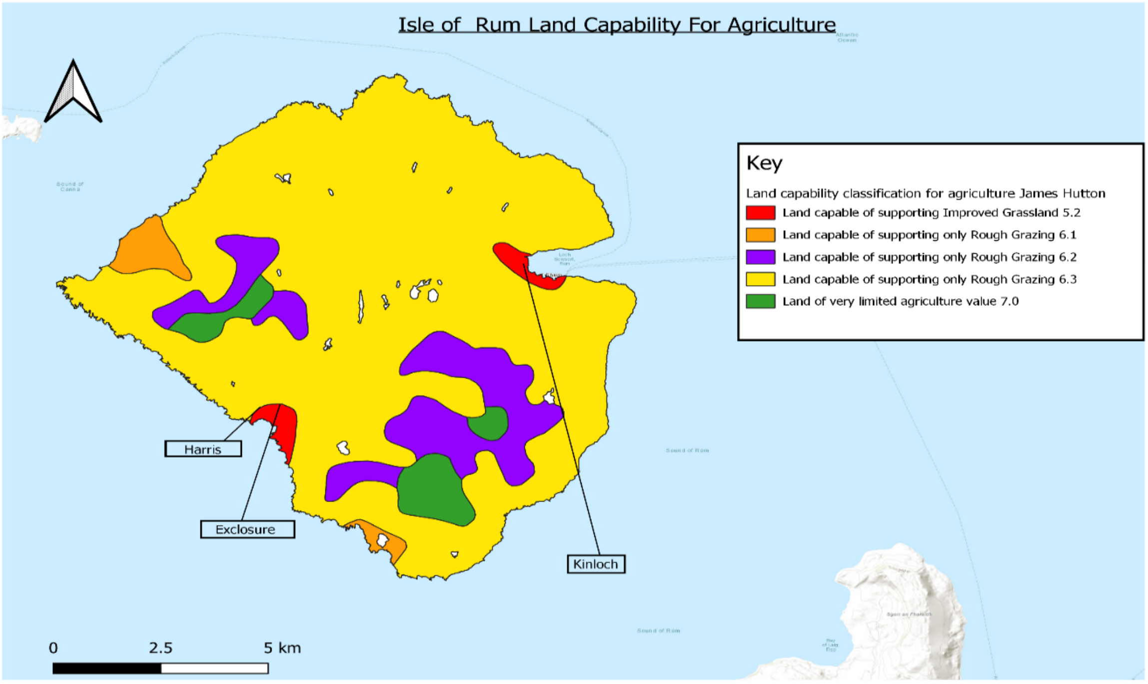

Figure 3 A land capability assessment map for the Isle of Rum (ESRI, 2023, Soil Survey of Scotland Staff 1984-87).

Agricultural policy is devolved to the Scottish Government, at present the Scottish Agriculture Bill is being developed which aims to make direct payments to farmers and crofters for food production with the caveat of adopting more sustainable practices such as protecting soils and at risk connected habitats. However, at the time of writing detailed plans regarding what this will practically entail for farming in Scotland are still in development (Scottish Government, 2024). This policy should help small scale food production systems, which inherently integrate a variety of ecosystem services into their operating model. This has led to a renewed interest in Lazybed systems and the value they could offer in issues regarding environmental benefits and sustainable food supplies for local populations (Butt & Nuutinen, 2021). However, current understanding of how Lazybed re-cultivation using kelp and dung-based fertilisers impacts upon ecosystem services is extremely limited. A recent pilot study (Knox et al., 2015) found there was scope to further investigate how Lazybeds could be re-cultivated for Scottish island communities.

Currently, cultivated Lazybed systems are rare in agricultural settings however, the system is still in use by hobbyists, research projects and interested parties mainly in Scotland and Ireland, naturally occupying a very small area of land (Dixon, 1994), which differs significantly from the area historically cultivated. Furthermore, as Lazybeds are by definition hand dug/constructed using a foot plough, this limits the size of land able to be cultivated, meaning areas of Lazybeds are too small to be included on land cover maps such as the Scotland Habitat and Landcover map which has a spatial resolution of 20 m^2 (Nature Scot, 2023). Highland and island populations and consequently the area of land likely under Lazybed production peaked during the 18th century. Pinpointing the exact total area of cultivated land in Scotland during the 18th century, is challenging due to limited comprehensive records from that time (Entwistle et al., 2000; Walker, 1980). Estimates and historical records suggest that a significant portion of the Scottish Highlands and islands was divided into Run Rig tenures for subsistence farming, but the exact acreage varies across different sources and regions (Dodgshon, 1998; Smith, 1994; Walker, 1812). The Run Rig system in Scotland historically involved small-scale agriculture, using Lazybeds among other farming methods ranging from just a few acres to around 15 acres (1-6 ha), and was characterised by a rotating tenure of the land in the township (Dodgshon, 1993; Guttmann et al., 2006). The land was typically divided into smaller plots, each used for different purposes such as growing crops, grazing animals, or harvesting peat for fuel (Darling, 1945). These plots were often worked by tenant farmers and their families for their own consumption, with any surplus sometimes sold for additional income (Dodgshon, 2015). Records from Rum in the 18th century indicated very little surplus production from the island with no grain exported and only enough produced to sustain the population with bread over winter (Walker, 1980). The Run Rig system was systematically replaced from the mid-18th century onwards by the crofting system, which used largely similar agricultural systems such as Lazybeds, but tenants occupied set parcels of land (Dodgshon, 1998).

Knox et al., (2015) demonstrated that sufficient seaweed could be harvested from the shoreline bordering a croft and that the harvesting rate would be sustainable if 1/6th of the total seaweed resource was harvested in one growing season based on a 6-year growth cycle, without adversely affecting the presence of seaweed. Cultivation methods employed in the study by Knox drew heavily upon historical records and oral traditions to understand and replicate the Lazybed practices. The research conducted experimental trials using different forms of seaweed (*Ascophylum nodosum*)- rotted, fresh, and a rain-washed seaweed liquor- to simulate a range of historical practices. While these methods might not precisely mirror historical practices due to logistical constraints and variations in the handling of seaweed, they aimed to mimic historical seaweed manuring practices found in records (Knox et al., 2015).This highlights the challenge of reconciling modern research methodologies with historical agricultural practices, highlighting the need for cautious interpretation of the findings. The findings emphasised the importance of incorporating seaweed and manure during establishment for improved crop yield. The study also highlighted the limitations of modernising these Lazybed cultivation systems, notably the absence of suitable mechanical equipment and the necessity for manual labour (Knox et al., 2015). This underscores the practical challenges of implementing historical agricultural practices in contemporary settings. This acknowledgment emphasises the importance of considering socio-economic factors and technological constraints in the development of sustainable agricultural strategies.

Furthermore, the study observed differences in crop yields due to variations in seaweed used. Rotted seaweed showed a notable increase in output, likely due to its influence on soil properties rather than its nutritional contribution. Changes in soil pH and observations of soil characteristics suggested potential impacts on microbial activity, soil structure, and nutrient levels (Knox et al., 2015). However, further research is needed to elucidate the specific mechanisms driving these differences and their broader implications for agricultural sustainability.

Overall, the study emphasised the complex interplay between historic agricultural practices, soil processes, and crop growth, shedding light on the importance of traditional knowledge in sustainable agricultural systems. The findings suggest that while modern adaptations are necessary, they should be informed by historical practices and tailored to local conditions for successful implementation of cultivation methods, particularly in relation to the use of seaweed as a fertiliser (Knox et al., 2015).

2.2 Agroecosystems and Ecosystem Services

Agricultural systems have the potential to provide multiple ecosystems services and sit within a landscape of wider ecosystem services. Ecosystem services, benefits provided to the human population by the natural environment and healthy ecosystems, can be divided into provisioning, supporting, regulating and cultural services (Corvalan et al., 2005).

Agricultural systems have traditionally been valued for the delivery of provisioning services; however, they are increasingly being recognised for their potential to support a wider range of services such as carbon storage, pollination, and nutrient cycling (IPBES, 2018). It is essential that the agricultural system, in focusing on food production, does not negatively impact other ecosystem services (Montoya et al., 2019). They supply food, fibre, and other agricultural products that sustain human life and support economies. Agroecosystems also contribute to supporting services by maintaining soil fertility, promoting nutrient cycling, and providing habitat for various organisms, which in turn aids in pest control and pollination (Barral et al., 2015). They also play a role in regulating services by influencing local climate, moderating water cycles, and mitigating the impact of extreme weather events such as floods or droughts (Birkhofer et al., 2021). These systems also hold cultural value, providing landscapes for recreation, maintaining cultural traditions related to farming practices, and offering a sense of place and identity for communities, this is particularly true for systems which have been historically associated with an area or peoples (Bernués et al., 2014).

Understanding and managing agroecosystems to optimise these ecosystem services is crucial for sustainable agriculture (Montoya et al., 2019). Balancing agricultural production with the preservation of supporting, regulating, and cultural services is essential to ensure the long-term viability of agricultural practices while minimising negative impacts on the environment (Muhie, 2022).

The degradation of ecosystem services will reduce yields and require further interventions. There is a renewed interest in Lazybeds and the value they could offer as solutions to increase food production on areas of marginal land, however, our understanding of how Lazybeds effect ecosystem services is extremely limited. From a cultural perspective the recultivation of Lazybeds offers a potential route to encourage communities back to the Scottish Isles and preserving a way of life that was nearly brought to extinction by the Highland Clearances. Further, for existing island communities increasing on-island food production makes these communities more resilient, when food supplies are disrupted e.g., bad weather preventing the delivery of food supplies to the island and poor infrastructure (BBC, 2023).

However, the concept of ecosystem services is critiqued by some as in agricultural systems it risks oversimplification by monetising complex ecological functions, potentially neglecting intrinsic and cultural values (Schroter et al., 2014). This framework often favours easily quantifiable services like crop production, sometimes at the expense of biodiversity and soil health. While useful, this concept requires a holistic approach to fully capture the complexity and multidimensionality of agricultural systems.

2.3 Historic Agricultural Practices: Lazybed Systems

As Agricultural methods became more advanced around 1000 AD, the Lazybed system was developed (Barber, 2001). Lazybeds (a type of ridge and furrow system) associated with small subsistence communities, consisting of parallel banks of ridges, up to 2.5 m across, and narrow furrows, dug with a spade, with their primary function to enhance drainage on marginal soils (Dodgshon, 2015; Smith, 1994) (Figure 4). Commonly cultivated crops in Lazybed systems included potatoes, barley, brassicas and legumes (Darling, 1945). In coastal communities, kelp, dislodged and brought ashore during storms, was often composted with animal dung and utilised as a soil amendment to increase fertility and subsequently crop productivity (Dodgshon, 2015; Entwistle et al., 2000) (Figure 4). Kelp (*L. digitata*) has a widespread distribution across the UK and is one of the most abundant macroalgae found in the lower intertidal and sublittoral zones. Key morphological features include digitate fronds, which become more numerate when exposed to greater levels of stress in the form of wave action, a stem-like stipe and a holdfast which anchors to bedrock and other hard substrates (Dring, 1992). Some Lazybeds employed a rotating management system, with land left fallow, often for periods equal to the length of time spent in cultivation (Dodgshon, 1998). The Lazybed system was commonly practiced and improved upon until the 19th century, when the Highland Clearances and potato famine resulted in the rapid depopulation of the Scottish Highlands and Islands (Dodgshon, 1998); leaving the areas of Lazybeds abandoned to become established by grasses and herbaceous vegetation heavily grazed by deer, cattle and goats from 1826 on Rum (SNH, 2018).

Figure 4 Historic photographs of (A) an area of land cultivated as Lazybeds and (B) a midden of kelp and animal manure in north west Scotland, which was utilised as a soil amendment to increase fertility and subsequently crop productivity (Fenton, 1976).

Surveys which aimed to characterise earthworm associations in agricultural landscapes (see section 2.5.4 for further information about earthworms and their relationships and interactions in agricultural landscapes) at Harris have also found the presence of 7 species, with populations dominated by *Aporrectodea caliginosa* (49%), *Lumbricus rubellus* (23%) and *Dendrodrilus rubidus* (19%) and that the populations are of a size demonstrated to have effects on soil nutrient cycling and plant growth (Butt & Nuutinen, 2021). The earthworm populations at Harris (richness of 7 species and abundance ranges of 24-112 individuals and biomasses 7.4 - 30.8 g m^2) also lie within the mid-upper expected range, based on an analysis of global earthworm distribution (Phillips et al., 2019).

Butt & Nuutinen (2021) also found that there was no difference in earthworm abundance between the ridge and furrows of historic Lazybeds, however, at another sampling site in North Uist, earthworm density and abundance was around 5 times greater in recently re-cultivated Lazybeds compared to the historic ones.

Parallels can be drawn between Lazybed systems and other ridge and furrow systems present globally throughout history (Retamero et al., 2016). Ridge and furrow farming is an ancient agricultural technique prevalent in Europe, Asia, and parts of Africa (Alcántara et al., 2017). This method involves creating raised ridges or mounds of soil separated by furrows or troughs. It was typically employed to enhance crop growth in areas with heavy clay soils, on soils that needed better drainage or in regions with limited access to suitable agricultural equipment (Retamero et al., 2016).

2.4 A Comparison of Current Agricultural and Lazybed Management Practices

2.4.1 Nutrient Management Organic Fertilisers: Manure and Marine Macroalgae

The use of inorganic fertilisers is thought to be a major factor is soil degradation (Jones et al., 2013; Khan et al., 2007), through effects on plant and soil fauna communities. Clover has long been utilised as a living fertiliser, traditionally co-planted in arable systems, as grassland leys, with its N-fixing bacteria converting atmospheric N into plant-available forms. However, when there is an imbalance of C and N inputs to the system (with more N input to the system, reducing the C:N ratio), as seen with inorganic fertilisers, the growth of clover, root nodule formation and thus its N-fixing properties decreases (Burchill et al., 2014). Moreover, N additions are strongly correlated to an increase in bacterial activity in the soil, which leads to a change (higher proportion of bacteria to fungi) in soil bacterial and fungal communities and can have a negative impact on key soil functions such as nutrient cycling, in addition to effects on soil fauna (Waring et al., 2013). The increase in bacterial activity in soils is associated with changes in soil texture and structure due to the mineralisation of soil organic matter (SOM) (Shao et al., 2022). Further changes to soil structure are induced by the reduction in soil fauna and the soil mycelium network, whose exudates and excretions bind soil in aggregates (Bearden & Petersen, 2000).

Given the nutrient holding capacity of SOM, and environmental impacts of inorganic fertilisers, it is illogical to add a source of nutrients without a co-input of organic matter. Animal manure has been utilised as a crop fertiliser in Europe, dating back eight thousand years (Bogaard, 2005). In the 20th century the development of inorganic fertilisers curtailed the common use of organic fertilisers, due to shifts in agricultural policy, the geographical separation of livestock and arable farming and also the significant initial gains in yield that were observed when inorganic fertilisers were first used in agricultural systems, which supported a growing global population and reduced rates of malnutrition (Williams et al., 2013). Due to the negative effects of inorganic fertilisers, there is a pressing need to reconsider the sustainable use of organic fertilisers, which helped maintain soil functions and food production for millennia. In addition to the plant macronutrients (NPK) found in inorganic fertilisers, organic fertilisers contain a wide variety of micronutrients to promote plant productivity, and augment SOM. This enhances soil quality and the efficiency of nutrient use in the system, ensuring minimal plant-available nutrients are lost from the ecosystem (Kidd et al., 2017). As energy sources in the form of plant residues in managed soils are often limited due to crop harvest, negative effects on soil microbial and fauna communities can be overcome through additions of energy and nutrient rich manures and composts. Earthworm, mite and collembolan populations have all been found to increase in systems where organic fertilisers have been added, which provides further benefits for plant productivity through impacts on nutrient cycling (Wardle et al., 2004). Organic fertilisers have also been shown to reduce the population densities of soil-borne pathogens and increase the densities of organisms which selectively feed on pathogens (Garbeva et al., 2004). *Phytophthora infestans*, the pathogen responsible for potato blight, has a reduced activity in soils where composts have been added (Zmora-Nahum et al., 2008). This is because compost promotes soil fauna which graze the oomycete and *Trichoderma* fungi whose metabolites function as a biocide against *Phytophthora* sp. (Bae et al., 2016). The turning over of soil in agricultural systems has both positive and negative effects. Potential benefits of Lazybed systems include increased soil aeration and drainage to benefit productivity through impacts on root respiration, weed control, improved seed beds, and reduced N_2O emissions in waterlogged soils (Panagos et al., 2015; Paul et al., 1999; Zhao et al., 2016). Whereas negative effects may include enhanced soil erosion and losses of soil organic carbon (SOC) and increased CO_2 and CH_4 emissions (Zhao et al., 2016). However, addition of organic fertilisers in tilled systems can reverse negative effects on SOC (Wall, 2013).

Soil organic matter (SOM) derived from plant, animal, fungal and bacterial organic structures at various stages of decomposition and synthesis, is a key component of soils, which promotes multifunctionality and plays a key role in physico-chemical and biological processes. Specifically, it acts as a sponge, holding nutrients and water in the soil structure. The residence time of SOM determines the overall content: a reduced residence time but no increased input of organic structures to the soil, will result in a decrease. A wide variety of factors are known to affect the residence time e.g., the type of organic input (plant communities), soil moisture and temperature, and land management strategies. SOM can be separated into two broad categories, ephemeral and recalcitrant (Janzen et al., 2022). Ephemeral (short-lived) SOM mainly denotes recently applied C inputs which are rapidly decomposed to CO_2. Recalcitrant SOM remains in the soil for a longer period of time, to serve as a soil carbon pool, enhancing soil carbon sequestration. It is thought that much of the recalcitrant SOM, is derived from microbial necromass stabilised through reactions with mineral compounds, a concept known as the microbial carbon pump (Liang, 2020). Further, changes in SOM observed under different land management strategies could therefore result in different inputs of plant derived organic matter to the soil, come from microbial necromass in the breakdown of this extra ephemeral soil organic matter (Zhu et al., 2020). Efficacy of the microbial carbon pump is in turn controlled by a variety of factors. One of these key factors is the composition of the soil microbial community, with fungal-dominated soils resulting in a larger pool of recalcitrant SOM (Liang, 2020). It is thus likely that additions of kelp to the soil system, will induce changes to the SOM pool, and increase resistance to reduced watering/drought by increasing hydrological buffering capacity of the soil. However, the extent of these changes in kelp-fertilised systems and their response to reduced watering/drought resistance, against comparable effects of traditional manure-based fertilisers is so far unknown. This is because the use of kelp as a fertiliser (as opposed to seaweed extract) is not currently a common practice in agricultural systems.

Coastal communities in northern and western Europe have long since recognised the benefits of using kelp and other marine macroalgae as a fertiliser to promote crop growth (Darling, 1945). Kelp is high in micronutrients, particularly calcium and iodine and generally has an NPK ratio of 1:0.2:2 (Lund Produce Company, 2018), additionally, it contains alginate, tannins and plant growth hormones. The high calcium content of kelp could act as a liming material increasing the pH of the soil, promoting better plant growth conditions through the binding of aluminium ions which dissociate in lower pH soils and have toxic effects on many plants (Tye et al., 2000). Iodine increases plant biomass production and promotes resistance to stressors (Medrano-Macias et al., 2016). Alginate acts to improve soil texture by binding soil aggregates and stimulates the production of plant growth hormones (González *et al.*, 2013). Kelp can be applied directly to soil as a mulch; however, some studies suggest that its properties are perhaps best enhanced when composted with animal manure (Entwistle et al., 2000). This is potentially because when kelp is mixed with animal manure, the fertiliser is bulked out with organic matter, leading to improvements in soil structure and water and nutrient holding capacity. In addition, phlorotannins, are polyphenolic compounds, commonly found in algae, which possess antimicrobial and anti-herbivory properties (Kubanek et al., 2004), that may help to protect crops from pests and diseases.

2.4.2 Water

Water is essential for plant health, from being required in photosynthesis to providing physical support (Hart, 1987). Plant productivity can be severely impacted by reduced watering conditions, reducing crop yields (Polley, 2002). The lack of moisture in the soil reduces the uptake of water by roots and stomatal conductance. This means that plants often input more energy into root growth in times of reduced water stress, reducing above ground growth (Sperry, 2000). A reduction in stomatal conductance reduces CO_2 uptake and thus photosynthetic capacity (Tuzet et al., 2003). Reduced water stress in plants can also negatively affect plant defence mechanisms, making the plants more vulnerable to pests and diseases (Takahashi et al., 2020).

Under climate change, the frequency and/or severity of drought events is likely to increase, placing production and economic stresses on UK agriculture (Wheeler & Lobley, 2021). Land use strategies are known to affect the drought resistance of a variety of crops (Vogel et al., 2012). A comparative study between effects of reduced watering on intensively managed wheat cropping systems in comparison to grassland systems, found that fungi were more resistant to reduced watering than bacteria (Birkhofer et al., 2021). Thus, in soils with fungal-dominated microbial communities, soil supported functions such as plant productivity are also more resistant to reduced watering (de Vries et al., 2023; Kaisermann et al., 2017). One of the main factors in determining whether a soil's microbial community is dominated by fungi or bacteria is the availability of nitrate (Birkhofer et al., 2021; Homyak et al., 2017). Thus, if kelp and dung fertilisers were used in Lazybed systems instead of inorganic fertilisers, it would be reasonable to assume that the microbial community would likely be fungal dominated and subsequently more resistant to reduced watering/drought (Januškaitienė et al., 2021).

It is important to understand whether differences in drought response exists between plants with the contrasting photosynthetic pathways, as it is understood that C4 plants are more efficient in their water use, due to their ability to continue photosynthesise when the stomata have closed and thus can be characterised as inherently more resistant to reduced watering/drought conditions (Lopes et al., 2011). The use of manure-based fertilisers to promote crop resistance to reduced watering has been displayed in both C3 and C4 photosynthetic pathway crops. Barley (C3) and millet (C4) were subjected to reduced watering conditions under current and warmed temperatures. Under both temperature regimes, the crops with organic fertilisers rather than inorganic fertilisers, had a reduced drop off in photosynthetic rate (Januškaitienė et al., 2021). Further, the production of enzymatic antioxidants in barley grown in warmed, reduced watering conditions, was 44% greater for organic fertilised crops. Further studies have found that the micro (Ca, Fe, Zn, S, Na, Mg) and macro (N, P, K) nutrient content, growth and physiological traits (plant height, leaf area, relative water content, membrane stability index, and chlorophyll) are negatively affected by reduced watering (Geremew et al., 2021), but, the use of organic fertilisers can ameliorate these impacts. These studies reveal that the type of fertiliser applied to crops can result in changes to the physiological and biochemical responses to reduced watering stress, resulting in enhanced resistance to reduced watering for crops treated with organic fertilisers (Geremew et al., 2021; Januškaitienė et al., 2021).

Alginate (Figure 5) is a hydrophilic compound and is found in the cell walls of brown algae such as *L. digitata. A*s an extract, it is widely used to improve water management, enhancing crop productivity, by reducing drought stress in crops and reducing water inefficiencies. Alginate functions to form a viscous gel, when bound with water. Alginate can be commercially extracted from algae and incorporated into growing media to improve water management. In horticultural systems the use of alginate-based hydrogels, has been found to result in an 80% increase in fresh mass of the plants grown in substrate supplemented with 5% hydrogels compared to control substrate after 7 days under reduced watering conditions (Tomadoni et al., 2020).

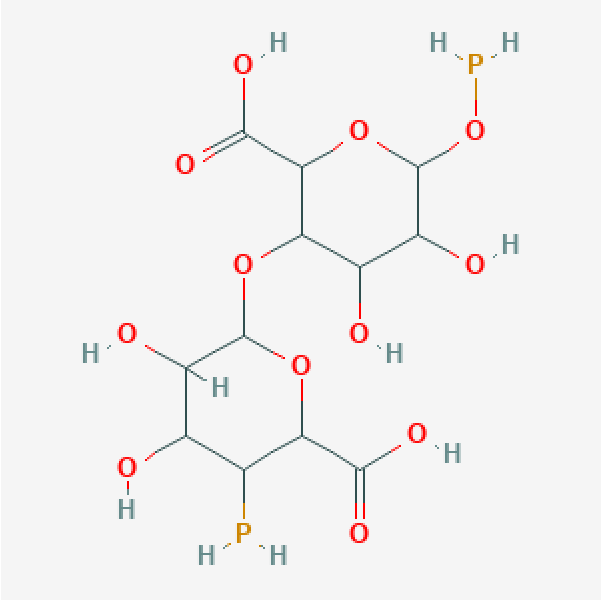

Figure 5 The chemical structure of alginate. The twelve hydrogen bond acceptors can be seen where water molecules can be bonded, to form a viscous gel substance.

2.4.3 Cultivation

Ridge and furrow farming, which includes Lazybeds, is an historic agricultural practice, which involves the creation of alternating raised beds (ridges) and sunken furrows (Myers, 2002). Historically, this technique has been used to improve soil conditions for crop growth, by improving the soil water balance in the rooting zone (Myers, 2002). Modern ridge and furrow farming has developed from the historic systems and is now used in the cultivation of a wide variety of crops as a water management method (Quinton et al., 2022). Specifically, modern ridge and furrow systems improve the soil water balance by reducing the impact of drought, improved soil aeration and drainage. Further, the turning over of the soil can act as a non-chemical weed control strategy (Brandsæter et al., 2017). These features support increased levels of productivity, improved environmental sustainability and cost efficiency (Li et al., 2019). In Malawi, deep bed farming (a form of ridge and furrow farming) is becoming widely practiced as a method to alleviate heavily compacted soils and deliver increased maize yields over common practices in the country (Mvula, 2021). The deep bed farming method is also more sustainable with soil losses reduced compared to conventional methods in the country (Mvula, 2021). Generally, intensive modern tilling processes have increased efficiencies and initially improved yields, however, it is projected that if changes in tillage practices are not implemented then crops such as winter wheat could see yields fall by 10 % over a century due to soil degradation (Quinton et al., 2022).

Tillage can have both positive and negative effects on soil structure (Gregory et al., 2015a). Initially, the act of tilling provides a physical mechanism to break up compacted soil, promoting percolation and improving conditions for germination/crop establishment. However, frequent and intensive tillage can lead to a degraded soil structure resulting in an increased risk of soil erosion and the loss of organic matter (Quinton et al., 2022). The degraded soil structure and loss of organic matter can result in decreased water and nutrient retention, ultimately affecting crop productivity (Quinton et al., 2022).

Tillage has traditionally been employed to control weeds by physically damaging the plants and exposing their rooting zones. Further during the act of tilling seeds from weeds may be transported to deeper soil depths where conditions for germination are less ideal. Therefore, tillage can be an effective weed control mechanism which can reduce the farming systems reliance on chemical herbicides (Brandsæter et al., 2017). While effective, this approach comes with consequences for soil degradation, as discussed above. Further, the environmental impact of tilling extends beyond soil degradation. The energy-intensive nature of mechanised tillage, often involving large tractors and equipment, contributes to greenhouse gas emissions in the agriculture sector (Balafoutis et al., 2017). Moreover, tilled fields are more susceptible to runoff, increasing the risk that diffuse agricultural pollutants namely, soil and agricultural chemicals enter water bodies, negatively impacting aquatic ecosystems and water quality (Stevens & Quinton, 2009).

Tillage practices have in many ways improved yields in modern agricultural systems, however due to the negative environmental practices it is important to explore alternative methods of crop production which promote sustainable environmental and food production outcomes (Gregory et al., 2015a).

2.4.4 Crop Science

The development of sustainable agricultural solutions requires accurate quantification of yield potentials. It would be false to claim a system to be sustainable if it could not meet the needs of the present in terms of food production (Handayani & Hale, 2022).

Advances in crop science over the last century have included the selective breeding, genetic modification and the use of fertilisers, pesticides, and herbicides to enhance yields (O'Brien & Mullins, 2009). More recently the development of high precision technology and the use of satellite data in crop monitoring software allows farmers to highlight variations in yields within a field allowing for highly targeted interventions to improve soil characteristics (Hedley, 2015). This targeted approach has the potential to reduce inputs, protect the environment and reduce the costs of production.

Further, advances in crop science now include the use of seed treatments and soil biologics. Seed treatments include a variety of techniques such as hormonal growth regulators, adjuvants, and pesticides (Procházka et al., 2015). Biologicals consist of microorganisms such as bacteria and fungi; beneficial macro-organisms (e.g., predatory mites); semio-chemicals (e.g., pheromones) or natural compounds (e.g., plant extracts) that can be used for the control of a wide range of pests and diseases while also making plants more productive (Bayer, 2020).

2.5 Biological, Chemical, and Physical Soil Properties and Functions (Nutrient Cycling)

Despite recent advances in our understanding of the interactions between soil fauna and ecosystem functions, large knowledge gaps persist (Briones, 2014; Filser et al., 2016; Wardle et al., 2004). Two key areas are how the activity and community of soil organisms regulates (i) nutrient cycling and (ii) primary productivity. The soil faunal community is made up of several interacting groups such as microbes, microfauna, mesofauna and macrofauna which, are thought to control ecosystem processes (Ingham et al., 1985), so there may be scope to manipulate these communities to benefit crop production in Lazybed systems.

Soil fauna can be distinguished through functional classification based on body width (Briones, 2014). Microfauna (< 0.1 mm) include nematodes, protists and rotifers; mesofauna (0.1 – 2 mm) are arthropods such as collembola and mites; and macrofauna (> 2 mm) include annelids, gastropods and macroarthropods (Orgiazzi et al., 2016). With reference to food web interactions, microfauna and mesofauna feed on bacteria and fungi and often fill the role of detritivore, partially breaking down organic residues which are then more labile to bacteria and fungi (Bezemer et al., 2010; George et al., 2017).

C and N cycling in soils is in part mediated by the presence and number of soil fauna groups/species (Briones et al., 2009; Lavelle et al., 1995). Top-down food web pressures from predatory soil organisms, who predate on lower trophic organisms which graze on fungi, such as collembola and mites, has knock on effects on C and N cycling (Wardle et al., 1995). Furthermore, the use of insecticides has been found to have deleterious effects on predatory soil organism populations, which could result in an increase in the populations of fungal-grazing soil organisms, which in turn negatively effects the fungal population and carbon storage capacity (Filser, 2002; Filser et al., 2002).

The home field advantage hypothesis states that decomposition rates for leaf litter are greater when the litter is decomposing in the vicinity of the plant species from which it was derived as opposed to decomposing beneath other plant species, due to the soil biological community composition and function (Ayres et al., 2009; Jacob et al., 2010). The enhanced decomposition rates for native litters, are likely to increase the concentrations of plant available nutrients in the soil profile (Veen et al., 2018). Research into Home field advantage is predominantly focused on how different fungal and bacterial communities break down leaf litter, however, home field advantage studies may also investigate soil fauna communities (Milcu & Manning, 2011).

2.5.1 Microbes

One teaspoon of soil contains around one billion microbes, from around 10,000 species (CEH, 2018). These fungi and bacteria are central to terrestrial ecosystem functions, such as crop fertility, pollutant removal, carbon storage and greenhouse gas (GHG) fluxes (Heijden et al., 2015; Manuel et al., 2016). With regards to crop fertility, microbes are responsible for the cycling of P and N in the soil (Van Der Heijden et al., 2008; Wood et al., 2015).

Arbuscular Mycorrhizal Fungi (AMF) establish symbiotic partnerships with approximately 80% of terrestrial plants, encompassing a diverse range of species such as potato, barley, oats, and legumes—all historically cultivated in Lazybed systems (Darling, 1945). This relationship between AMF and plants is mutually beneficial: the fungi function as essential nutrient conduits, to uptake nutrients from the soil and transfer them to the plants, while the plants provide sugars to fuel the fungal metabolic processes (Paola & Andrea, 2010).

Of particular interest is the synergy observed in legumes, which form tripartite symbiotic associations involving nitrogen-fixing bacteria and AMF. This allows legumes to optimise nutrient acquisition strategies by harnessing nitrogen from the bacteria and phosphorus from the AMF, further enhancing their growth and development (de Varennes & Goss, 2007).

Moreover, AMF have been found to significantly influence soil respiration rates. Notably, in environments where fungal communities dominate, lower soil respiration rates are observed compared to that of bacterial dominated soils (Zhang et al., 2016). This suggests that the presence and prevalence of AMF in soil ecosystems have notable impacts on fundamental soil processes, potentially affecting carbon dynamics and overall ecosystem functioning.

The multifaceted relationships between AMF, diverse plant species, nitrogen-fixing bacteria, and soil processes highlight the intricate web of interactions in terrestrial ecosystems. Understanding these symbiotic associations not only elucidates plant nutrition strategies but also underscores the broader implications for nutrient cycling, carbon dynamics, and ecosystem productivity.

The decomposition of organic matter, a key process in the plant-soil nutrient cycle is generally considered to be dominated by microbial processes in temperate ecosystems (Bani et al., 2018).

Microbially-mediated decomposition is primarily determined by climate, litter quality and soil chemical, physical and biological properties (Cortez, 1998; Filser et al., 2016). Litter in the preceding sentence refers to senesced plant material such as leaves, which fall to the ground and form a layer of decomposing detritus. Leaf litter is an important component of soil health, acting as a source of nutrients which are transferred into the soil through its decomposition and improving structure and soil-hydrological properties. The plant species from which the litter is derived determines the quality of this litter and how labile or recalcitrant it is in its decomposition (Austin et al., 2014). For example, if the litter possessed a high lignin or a reduced N content it could be characterised as poorer quality and recalcitrant, as decomposer communities find this less palatable (Melillo et al., 1982). However, it is unclear which of these factors are the determining controls over microbial decomposition (Aerts, 1997). Temperature and moisture, generally positively correlate to increased rates of microbial decomposition (Curtin et al., 2012). However, microbial activity is inhibited when temperature and moisture thresholds are reached (Freeman et al., 2001; Sinsabaugh, 2010). Currently, evidence indicates that the primary factor determining microbial decomposition rates, may be the composition of the vegetation community, with changes observed with the type and number of plant species, due to differences in the quality and quantity of leaf litter and root exudates, and associated microbial communities (Lamb et al., 2011; Ward et al., 2015). Carbon-to-nitrogen ratios (C: N), lignin composition and nutrient content are key determinants of microbial decomposition rates. Microbial decomposition has been found to increase with nutrient status and lower C:N ratio, and higher concentrations of lignin inhibit microbial decomposition. These controls on the decomposition of organic matter in terrestrial ecosystems in turn determine the movement and storage of carbon in the biosphere (Aerts, 1997; Bakker et al., 2011)

The decomposition of organic matter in terrestrial ecosystems, primarily controlled by microbial processes, is a complex interplay of various factors (Bakker et al., 2011). While climate, litter quality, and soil properties play crucial roles, recent research indicates the substantial influence of vegetation community composition on decomposition rates (Cortez, 1998). Understanding the role of leaf litter quality in decomposition processes is vital for predicting nutrient cycling, carbon sequestration, and overall ecosystem functioning (Aerts, 1997). Further research elucidating the relationships between leaf litter traits, microbial communities, and environmental conditions is needed to deepen our understanding of this fundamental ecological process (Aerts, 1997). In the context of this thesis, parallels can be drawn between the decomposition of leaf litter and the incorporation of organic fertilisers into soils. By furthering understanding of decomposition and nutrient cycling agricultural systems can be developed to work with these natural processes leading to better soil water and nutrient balances, and improved resilience to climatic perturbations, contributing to global food security.

The relative abundance of bacteria and fungi in the soil regulates the carbon cycle through their relative "fast" and "slow" energy channels (de Vries & Shade, 2013; Van Der Heijden et al., 2008; Yu et al., 2022). In grassland systems with high functionality, fungi dominate the soil microbial population. In contrast, in degraded grassland and arable soils, bacteria are often found to be dominant (Ushio et al., 2013). In non-degraded soils, the asymmetry in energy flux, due to the dominance of fungi, increases the resistance and resilience to perturbations. The r/K selection theory can also be applied to soil microbial communities (de Vries & Shade, 2013). In this theory, r-strategists such as bacteria are opportunists in resource-rich environments with rapid growth characteristics and K-strategists such as fungi, are slow growing in low nutrient conditions (Grime, 1974, 1977; Grime, 1979; Yin et al., 2022). The ratio of r-strategists and K-strategists in soil microbial communities can impacts soil processes, including nutrient cycling, in a variety of ways. In soils where nutrients are non-limiting, r-strategists tend to dominate, leading to the rapid decomposition of organic matter and nutrient release (Pan et al., 2022). Whereas, in soils which are low in nutrients, K-strategists tend to be more prevalent (Adomako et al., 2022). Microbial communities can influence soil structure through their exudates and impact on organic matter content of the soil. The dominance of r-strategists might lead to a decline in soil structure, due to the loss of organic matter, through rapid decomposition, while K-strategists may contribute to more stable soil conditions, as their exudates promote the formation of soil aggregates (Sun et al., 2021). Understanding the dynamics between r- and K-strategists in soil microbial communities provides insights into how microbial populations respond to changes in nutrient availability and environmental conditions, ultimately influencing nutrient cycling in the soil ecosystem and in turn plant growth (Zhang et al., 2023). Ecological resistance and resilience are enhanced due to fungi increasing the amount of organic matter in the soil system, in turn increasing nutrient availability and benefiting water regulation, features which are essential in crop production systems (Jia et al., 2021). The shift towards more intensive agricultural practices has resulted in a change to bacterial-dominated grassland food webs (Martínez-García et al., 2017). The shift observed in intensive agricultural systems is likely due to increases in N availability, with bacteria displaying opportunistic, fast response traits to excess nutrient inputs or practices such as tillage which damages the mycelium network releasing a flux of nutrients in to the soil system (Orrù et al., 2021). However, caution with this interpretation is required: one of the main critiques of r/K selection theory and "fast" and "slow" energy channels, collectively referred to as soil microbial ecology theories from hereon in, is the oversimplified categorisation of groups/species into either R-strategists or K-strategists based on a few aforementioned key traits (Reznick et al., 2022). While these generalisations provide a useful framework, they often fail to capture the complexity and variability within species and ecosystems.

Despite the importance of microbes, our understanding of their diversity, function and interactions is extremely limited. An improved understanding could be utilised to better manage land for sustainable crop production.

2.5.2 Microfauna

Soil microfauna, including nematoda, protozoa and rotifera, promote nutrient cycling and plant productivity through feeding on fungi, bacteria and rhizodeposits. By consuming specific groups of soil microbes, soil microfauna can promote the competitive advantage of beneficial microorganisms i.e., nitrogen-fixing bacteria and arbuscular mycorrhizal fungi (AMF). Some nematodes and protozoa have been shown to increase vegetation N content by 14% (Griffiths et al., 2011). Further, the addition of organic fertilisers has been shown to increase nematode populations in soils (Ingham et al., 1985). Therefore, potential feedbacks may occur between nematodes and fertiliser applications to further enhance N uptake by plant.

Nematodes are the most abundant animals present in soils: a single gram of soil can be home to hundreds of individuals. Due to their abundance and range of trophic levels in the soil food web, nematodes are key to many soil functions and can be useful as indicators of soil fertility as their role is beneficial in the cycling of nutrients (Van Den Hoogen et al., 2019). Soil carbon content closely correlates with nematode abundance: modelling predicts that Rum soils will have a relatively high nematode abundance (Van Den Hoogen et al., 2019), providing a good foundation for soil functionality.

2.5.3 Mesofauna

Collembola, diplura, enchytraeides, mites, protura and tardigrades, are the most abundant groups in the soil mesofauna community (George et al., 2017). Soil mesofauna are also used in research as indicator species, as they are widespread, representative, functionally important and responsive to changes in biotic and abiotic conditions (Chapman et al., 2023). Collembola and enchytraeides may be of particular interest to this thesis, due to existing research which has demonstrated their role in seashore ecosystem processes namely macroalgae decomposition (Sveum, 1987). Collembola feed exclusively on fungi, bacteria and algae hence, implicating a role in the decomposition of kelp fertilisers. Enchytraeides which are particularly abundant in wet highly organic soils commonly found on Rum, are responsible for processing large quantities of soil and dead plant material, indirectly enhancing microbial activity, decomposition and nutrient cycling (Cole et al., 2000).

Existing research demonstrates the considerable influence of more conventionally applied organic matter on collembola populations (Pommeresche et al., 2017). Specifically, collembola play a pivotal role in processing conventionally applied organic manures, such as animal manure, thereby enhancing soil nutrient status to support crop growth (Miller et al., 2017). However, the interaction between collembola and organic fertilisers and their impact on crop growth differs notably from that of inorganic fertilisers (Zhou et al., 2022). While inorganic fertilisers provide plants with readily available nutrients, resulting in rapid nutrient uptake, organic manures decomposed by collembola release nutrients gradually (Wang et al., 2016). This slow release of nutrients can support crop growth for longer periods, whereas inorganic fertilisers will require regular reapplication in the growing season to sustain crop growth (Maltais-Landry et al., 2019).

2.5.4 Macrofauna

Soil macrofauna includes annelids, gastropods and macroarthropods. Numerous studies have demonstrated the role of soil macro fauna in leaf litter decomposition and soil nutrient cycling processes (Bezemer et al., 2010). Soil-dwelling macro fauna, including earthworms, millipedes, woodlice, and larger arthropods such as carabid beetles, play a key role the breakdown of leaf litter and thus nutrient cycling within terrestrial ecosystems (Paoletti & Hassall, 1999). These organisms, through various mechanisms, accelerate decomposition rates by fragmenting leaf litter, enhancing microbial activity through gut passage and casting activities, and increasing surface area for microbial colonisation (Briones, 2014). Earthworms, for instance, through their burrowing and feeding activities, facilitate litter breakdown (Nichols et al., 2008) by promoting microbial decomposition and nutrient mineralisation (Liebeke et al., 2015). Similarly, woodlice and millipedes, by shredding and fragmenting leaf litter, aid in accelerating decomposition rates (Paoletti & Hassall, 1999). The effect of these soil macrofauna on leaf litter decomposition underscores their pivotal role in nutrient cycling and organic matter turnover within ecosystems, ultimately improving soil nutrient availability and crop productivity (Costantini et al., 2018). Similarities can be drawn between the role of macrofauna in leaf litter decomposition and the incorporation of organic fertilisers to soils. Research has confirmed that some soil macrofauna do influence yields and that their presence contributes to the sustainability of the agricultural system (van Groenigen et al., 2014). Further, these groups of soil fauna are impacted by management. Specifically, Coleoptera are affected by synthetic N application (Makwela et al., 2023). Carabidae (Coleoptera), are extensively used as indicators of ecological health/functioning.

They are mainly predatory and their position higher up the food web can be used to assess the populations of lower trophic groups and make inferences on nutrient cycling (Toivonen et al., 2022)

Dung beetles (Geotrupidae and Scarabaeidae) also play a crucial role in nutrient cycling within the UK ecosystem (Hutton & Giller, 2003). Dung beetles feed on and break down animal dung, thereby facilitating the decomposition process (Nichols et al., 2008). Through the action of burying dung and moving through the soil, beetles incorporate dung into the soil profile, this introduces organic matter and associated nutrients to the soil, which in turn promotes plant growth (Evans et al., 2019). Overall, dung beetles in the UK are integral to well-functioning soil systems promoting sustainable crop production (Nichols et al., 2008).

Earthworms (*Annelida*) are ecosystem engineers; species which modify, maintain or create habitats (Forey et al., 2018). Earthworms can be classified into three ecological categories dependent on their burrowing activity (epigeic, endogeic or anecic) (Bouché, 1972). Epigeic earthworms mainly feed on the leaf litter layer, with their population size positively correlating to decomposition rates (Muys et al., 1992). Most of the organic matter consumed by these earthworms in the humus layer is egested to the soil environment (Cortez, 1998). Geophagous, endogeic earthworms burrow horizontally in the soil, where they live, deriving their food directly from the soil and microbes within. Anecic earthworms make permanent vertical burrows in the soil, coming up to the surface and pulling organic materials down into the soil to feed (Curry & Schmidt, 2007). Anecic earthworms at some locations are responsible for the majority of litter burial. Further, some soil from depths is brought to the surface by anecic species in castings (egestion) (Bentley et al., 2024). However, anecic species incorporate plant material into the soil, increasing rates of soil formation and can play a role in soil carbon sequestration. Without earthworms, rates of leaf litter decomposition are suppressed, which in turn affects the turnover of nutrients in the system, key in the promotion of plant growth. Burrowing action by anecic and endogeic earthworms significantly alters soil structure, reducing compaction and increasing water infiltration with flood mitigating effects (Kiss et al., 2021). Furthermore, soil which has come into contact with an earthworm, interacts with intestinal and cutaneous mucus. The compounds in the mucus create a priming effect increasing soil microbial activity (Lavelle et al., 1995). However, after the initial priming effect, C is protected in stable aggregates within earthworm castings (Brown 2000).

Positive effects of earthworms on plant growth are well documented; however, understanding the mechanisms underpinning increases in productivity are currently incomplete. To encourage earthworms to maximise positive impacts on agricultural productivity, it is essential to further understand how earthworms interact with abiotic and biotic factors to affect ecosystem functions. A wide variety of factors such as climate, soil properties, crop types, earthworm communities and farm management practices, may affect the impact of earthworms on crop productivity. A number of possible pathways for how earthworms stimulate plant growth have been proposed (i) biocontrol of pests and diseases; (ii) stimulation of microbial plant symbionts; (iii) production of plant growth regulating substances; (iv) regulation of plant defence mechanisms; (v) soil structure changes; and (vi) increased nutrient availability (Scheu, 2003; van Groenigen et al., 2014). Of these, changes in soil structure and nutrient cycling are thought to have the largest effects sizes. Specifically, it is increased N mineralisation from crop residues and soil organic matter through earthworm activity which leads to increases in plant growth. This is supported by studies which found that earthworms have no significant effect on legume crops, or on pastures with legumes present (van Groenigen et al., 2014). More recently research by (Fonte et al., 2023) has found that globally, earthworms contribute to 2.3% of legume production, however this is significantly lower than the 6.5% contribution to grain production and likely due to the aforementioned effects of N mineralisation as reported by (Fonte et al., 2023; van Groenigen et al., 2014). The effect of earthworms on P availability and in turn plant growth is unclear. P availability in earthworm casts has been found to increase, however, this has not yet been found to affect plant growth. Furthermore, legume crops which have higher P demands did not show positive effects of earthworm communities on plant growth (van Groenigen et al., 2014).

The distribution of earthworms at a global scale is predominantly determined by climatic factors; with precipitation regimes being the most important (Fierer, 2019; Guerra et al., 2019; Phillips & De Vries, 2019). On the Isle of Rum, models predict that earthworm abundance and biomass were relatively low (Guerra et al., 2019). This can in-part be associated with the legacy effects of glaciation, low litter inputs and low soil nutrient content. Earthworm surveys of Rum have found a highly variable spatial distribution, with earthworm populations located mainly in areas of previous agricultural use, whereas other areas of the island have very low populations (Butt & Lowe, 2004). Further it is likely that many earthworms were transported from mainland Scotland for use in the manor gardens. However, at Papadil, Rum, a population of *Lumbricus terrestris* has been identified as the largest earthworms in the UK, weighing up to 12.7 g and measuring 40 cm in length. Unique ecological factors are thought to have driven this change in adult size, including high soil fertility in comparison to the rest of the island and the absence of predators, which allows worms to live to around 10 years old, rather than an average year or two (Butt et al., 2016).

Plant productivity in many cool, waterlogged systems is generally N-limited. Many historic Lazybed systems are situated on soils characterised as peaty gleyed-podsols, which are nutrient deficient due to low temperatures limiting microbial activity, resulting in a deep organic layer (James Hutton Institute, 2019). Within this layer many nutrients are locked up. A recent study has found that plant-soil N cycling in arctic systems, is further limited by the absence of earthworms (Blume-Werry et al., 2020). However, recently introduced invasive earthworms have also been found to unlock nutrients in forest soils at Northern latitudes, resulting in a loss of carbon stocks (Blume-Werry et al., 2020; Lejoly et al., 2021). Many nutrients in the organic layer became more bioavailable due to earthworm action following introduction. Specifically, it is the mineralisation of N in litter and humus, coupled with the translocation of nutrients in the soil profile to root zones. Where earthworms were present pant N concentrations increased which led to increased plant height, floral shoot numbers, vegetation greenness and fine root biomass in shrubs and grasses. Interestingly, this study also found that earthworm effects on plant N and greening were greater than observed effects of nutrient additions from reindeer urine and dung additions (Barthelemy et al., 2018).

The palatability of macroalgae to earthworms needs to be considered to fully assess the potential for the sustainable recultivation of Lazybed systems. Other studies have demonstrated how the growth potential of earthworms is affected by the species of macroalgae and earthworm (Butt et al., 2020). Specifically, earthworm mass gain was greater with kelp (*L. digitata*), over serrated wrack (*Fucus serratus*). However, earthworm mass gain was greater with conventional earthworm foodstuffs namely birch leaves and horse manure (Butt et al., 2020). Choice chamber experiments showed preference to the nitrogen-rich conventional foodstuffs, and when only offered macroalgae, *Lumbricus rubellus (epigeic)* and *Aporrectodea longa (anecic)*, showed a strong preference for kelp over serrated wrack.

The effects of earthworms on soil functions could be essential in meeting the challenges of sustainable intensification (van Groenigen et al., 2014), to enhance global food security for a growing population and reduce negative environmental impacts of agricultural systems. Positive effects of earthworms on plant growth are well documented (Scheu, 2003), however, understanding the mechanisms underpinning increases in productivity are currently incomplete. In utilising earthworms to maximise positive impacts on agricultural productivity, it is essential to explore how earthworms interact with abiotic and biotic factors that affect ecosystem functions. The role of earthworms in agricultural systems is complex and context-dependent with variable effects on crop yields, and interactions with modern agricultural practices. A nuanced approach that considers the specific species, local soil and climatic conditions, and sustainable management practices is essential to fully assess the potential benefits of earthworms.

2.6 Project Knowledge Gaps

Despite recent advances in understanding of the interactions between soil fauna and ecosystem functions, large knowledge gaps persist (Briones, 2014; Fisler et al., 2016; Wardle et al., 2004). A key area of the current research set out to investigate how the activity and community of soil organisms regulates nutrient cycling and primary productivity. The soil fauna community comprises several interacting groups such as microbes, microfauna, mesofauna and macrofauna which, in conjunction, are thought to control ecosystem processes (Ingham et al., 1985). As such, there may be scope to manipulate some of these soil faunal communities to benefit crop production in Lazybed systems. Specifically, due to their role as ecosystem engineers and the extensive body of literature in relation to their role in conventional agricultural systems, earthworms warrant particular attention. Moreover, unlike many other soil organisms, earthworms due to their size can easily be manipulated for experimental purposes. Further, it is unclear how traditional Lazybed practices, such as the addition of kelp fertilisers and unique ridge and furrow system, may impact on soil properties and subsequently crop productivity under a range of climate scenarios. This could offer insights into how kelp performs as a fertiliser when compared to more traditional organic amendments such as manure and whether growth responses differ by crop type. Aims to address these knowledge gaps are presented in the introduction, alongside detailed objectives and hypotheses for each experimental chapter.

3. Effects of Kelp and Dung Fertilisers on Crop Production in Lazybed Systems

3.1 Introduction

The importance of soil functions and the services these functions provide in food production systems cannot be stressed enough. Soil is an exhaustible resource and has witnessed accelerated degradation since the advent of intensified agricultural practices, posing a significant challenge to achieving sustainable food production (Gomiero, 2016). Factors contributing to this degradation encompass the loss of organic matter through land-use change, vegetation removal, soil disturbance, erosion through various natural processes, contamination, compaction caused by machinery and high stocking densities, and acidification from atmospheric pollutants (Kraamwinkel et al., 2021).

Soil erosion has serious implications for agriculture and poses a threat of pollution to the wider environment, resulting in the abandonment of approximately twelve million hectares of land annually worldwide (Gibbs & Salmon, 2015). Inorganic fertilisers are sometime used in response to soil degradation, in an effort to maintain crop yields (Gomiero, 2016). However, the use of inorganic fertilisers and pesticides are known to be environmentally damaging and can reduce crop resistance to disease and create feedbacks (Macary et al., 2014). Nitrogen is considered to be the element most limiting to primary productivity (Franche et al., 2009, Daughtry et al., 2000) and is essential in plant growth (Russell, 1973). The mineralisation of nitrogen is the process that converts the N in organic compounds into plant-available nitrogen in the form of ammonium and nitrates and this conversion is completed through soil microorganisms in the form of symbiotic bacteria and fungi (Russell, 1973, Cassada and Russell, 1975, Xu et al., 2012).

In theory, soil fertility the relationship between yields and fertiliser application can be explained through i. the nutrient balance of the soil, relating the levels of nutrients in the soil to the fertiliser inputs and losses to the environment, either through transport in water, speciation to gaseous forms, and processing by soil microbes and fauna; ii. the nutrient uptake efficiency of the root system and; iii. the crop nutrient requirements (Reynolds & Haubensak, 2009; Smith et al., 2019). This should mean that the effects of adding fertilisers result in changes to soil properties, which in turn affects the uptake by plant roots and plant nutrition.

Soil health as a concept is seen as an extension of soil fertility and soil quality which considers biological, physical and chemical soil properties and how these relate to the sustainable provisioning of ecosystem services such as crop production (Harris et al., 2022). To be sustainable, systems need to manage soils so as to not affect their future functioning in a negative way i.e., does not degrade the soil or cause wider environmental damage, maintaining soil health (Handayani & Hale, 2022).

The advent of modern agriculture has in many ways increased food security; however, the sustainability of many of the methods currently employed is unclear and may be leading to reversals in original advances in food security (Jones et al., 2013). The extensive use of inorganic fertilisers, pesticides, heavy machinery etc. has contributed to soil degradation and threatens ecosystem services provided by soils such as food production (Gregory et al., 2015a). 970 million tonnes of soil are lost each year in the EU, with losses from arable land equating to over 40 % (Panagos et al., 2015). In the UK, soil degradation costs £1.2 bn per year, mainly due to losses of organic matter, compaction and erosion (Graves et al., 2015). The loss of organic matter which accounts for 47% of the economic losses is attributed to an increased requirement for irrigation systems, inefficiencies in fertiliser use and yield reductions due to lower water and nutrient holding capacity of the soils (Gregory et al., 2015a). Ex situ, losses of organic matter from soils resulted in economic costs on account of its effect on greenhouse gas emissions, flood mitigation and drinking water contamination (Graves et al., 2015). Over the years as soils have become degraded, to combat decreases in yields many farms have further tried to intensify their production methods (e.g., using more inorganic fertilisers), which creates positive feedbacks leading to further soil degradation and decreasing the sustainability of food production (Mulvaney et al., 2009).

Clover (*Trifolium*) sp. have long been utilised by farmers as a living fertiliser, traditionally co-planted in arable systems, with its N fixing bacteria converting atmospheric N into plant available forms (Ladha et al., 2022). However, when there is an imbalance of C and N inputs to the system, as seen with inorganic fertilisers, the growth of clover and thus its N fixing properties decrease (Burchill et al., 2014). Further, N additions are strongly correlated to an increase in bacterial activity in the soil, this leads to an imbalance between soil bacterial and fungal communities which can have a negative impact on key soil functions such as nutrient cycling as well as affecting soil fauna (Waring et al., 2013). The increase in bacterial activity in soils is associated with changes in soil texture due to the mineralisation of soil organic matter (Shao et al., 2022). Further changes to soil structure are induced by the reduction in the soil mycelium network and soil fauna, whose exudates and excretions bind soil in aggregates (Guhra et al., 2022). Moreover, in historic systems such as Lazybeds, it is likely that clover species would have naturally colonised Lazybeds from the existing seed bank during ley periods. In fact, it was noted by Darling (1945) that the most productive Lazybeds also had white clover (*Trifolium repens*) growing on them. Vegetation assessments on areas of historically cultivated Lazybeds have confirmed the presence of legumes, adding further evidence to support this (Appendix 9.1).

Given the nutrient-holding capacity of soil organic matter (SOM), the addition of organic matter alongside nutrient sources is crucial (Blair et al., 2006). While inorganic fertilisers gained prominence, their adverse effects have underscored the urgency to revert to sustainable organic fertilisers, historically instrumental in maintaining soil functions and food production for centuries, albeit at a much lower population level (Bogaard et al., 2013). Organic fertilisers not only supply plant macro and micronutrients but also augment SOM, benefiting soil quality and nutrient efficiency while promoting soil fauna populations, with all these functions supporting plant growth (Axelsen and Kristensen, 2000; Topoliantz et al., 2002).

In areas with marginal soils, land management techniques, e.g., Lazybed systems were employed to create more suitable growing conditions (Darling, 1945). Lazybeds are a type of ridge and furrow agricultural system, which historically was commonly practiced by Scottish island communities and subsistence farmers, however examples can be found across Britain and Ireland (Foster & Smout, 1994). Lazybeds consist of parallel banks and ridges dug by hand generally on marginal soils with the aim of improving conditions for crop growth (Nature Scot, 2019). These systems often used locally sourced marine macroalgae and animal manures to support nutrient levels in the soils (Darling, 1945; Entwistle et al., 2000). Furthermore, the historical use of kelp in coastal communities as a fertiliser, rich in micronutrients and plant growth hormones (Haslam & Hopkins, 1996), offers potential as a soil amendment to enhance fertility and crop productivity. Its combination with animal manure could potentially mitigate negative tillage effects on soil organic carbon (SOC) in ridge and furrow systems (Dodgshon, 2015; Entwistle et al., 2000). Yet, evaluations comparing kelp's effectiveness against other organic and inorganic fertilisers remain scarce. This chapter will refer to Lazybed Systems which encompasses the physical structures but also associated management practices e.g., macroalgae fertilisation.

The series of experiments presented in this chapter aim to increase our understanding of historic management practices, such as those in the Lazybed system, including the use of kelp as a fertiliser. This chapter employed a range of approaches, with field studies using recultivated and newly created Lazybeds, and glasshouse and garden experiments to try to further disentangle the effects of kelp fertilisers on plant growth in a controlled environment. Specifically, this chapter seeks to make initial assessments of how potatoes, a traditional Lazybed crop, grow in a Lazybed field system under a variety of traditional fertiliser treatments. To further support this, a range of experiments were conducted to assess how the use of kelp fertilisers and their method of application and processing affected outcomes for plant growth on a variety of crops, inducing changes to soil properties. A range of hypotheses were evaluated in this chapter and are set out below by experiment.

Experiment 3.1.

It is hypothesised that the use of kelp and manure as fertilisers affects the production of potatoes in recultivated Lazybeds.

Experiment 3.2

It is hypothesised that fertiliser origin and processing treatments affects the production of potatoes in newly created Lazybeds.

Experiment 3.3

It is hypothesised, that the relationship between kelp additions and crop productivity is logarithmic, tending to a point of optimum application rate and that by using a gradient method (Kreyling et al., 2018), it is possible to determine this rate more accurately.

Experiment 3.4

It is hypothesised that an increased application of kelp fertilisers affects the growth of lettuce, although a point is reached where no further impacts on growth with increases in fertiliser applications are observed.

Experiment 3.5

It is hypothesised that as kelp becomes more decomposed this affects plant growth.

3.2 Methods

This chapter comprises of five experiments. The experiments are presented sequentially, and aspects taken from the earlier work influenced the design of the subsequent experiments. This approach was adopted due to the extremely limited existing work into Lazybed systems and the use of marine macroalgae as a fertiliser (Knox et al., 2015). Once it became apparent that kelp performed equal to, or better than conventionally derived animal dung/manures (in promoting crop growth), the experiments in this chapter and proceeding chapters focused on assessing the role of kelp as a fertiliser and how its use may be optimised. The overarching theme of this chapter is to elucidate how different organic fertiliser types affect crop growth in field trials, which is then supplemented by three further laboratory experiments to determine optimal application rates and pretreatment of fresh kelp fertilisers. A range of crop types (potatoes, lettuce, and spring barley) were selected for experimentation, this was intended to give an indication of the efficacy of fresh kelp as a fertiliser in a range of systems and for crops with a range of growth forms. Despite the absence of historical records detailing the use of Lazybeds for lettuce cultivation, lettuce is currently a prevalent crop in Scotland, particularly in areas where conditions are favourable. Communities are actively encouraged to engage in lettuce cultivation as part of sustainability initiatives (Sustainable Uist, 2012). In addition, lettuce was chosen due to its rapid growth thereby shortening the experiment.

3.2.1 Yields

In Experiments 3.1 and 3.2, potato yields were determined by weighing individual tubers from each plant in each treatment plot. Prior to weighing, the tubers were washed in clean freshwater and dried with absorbent roll.

In Experiments 3.4 and 3.5, lettuce yields were determined by weighing the freshly harvested above ground lettuce body. Further measurements were also taken of below ground biomass, by carefully washing the roots to remove soil particles, weighing, drying the root biomass in an oven at 60 ^{o}C until a constant mass was reached, then weighing again (Rowell, 2014).

Due to the onset of the COVID-19 pandemic an early cessation occurred of Experiment 3.3, prior to ear formation, so it was not possible to determine crop yields, instead, the shoots and roots were separated and measured as above ground biomass and below ground biomass respectively. Both samples then had masses determined after drying in an oven at 60 ^{o}C for 48 hours.

3.2.2 Soil, Fertiliser and Plant Properties

A range of soil properties were measured in the experiments detailed above. Soils were sub-sampled to assess for moisture and carbon content, C:N, pH, nitrate and micronutrient analysis. In the preliminary experiment (see appendix 9.1 and 9.2 for details) nitrate, ammonium and phosphate were assessed, using a KCl extract (for inorganic N) and $NaHCO_3$ respectively, prior to analysis on a spectrophotometer. These sub-samples were first passed through a 2 mm sieve, oven-dried at 105 °C until a constant mass was reached, then placed in a furnace at 535 °C for 4 hours to determine moisture content and loss on ignition ((LOI) to give an indication of organic carbon content), respectively (Rowell, 2014). The pH was determined by adding 5 g +/- 0.1 g of substrate to a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), plus 25 ml of deionised (DI) water, inverted at 5-minute intervals for 30 minutes, then the liquid phase filtered through Whatman no. 1 and measured using a Hanna Edge probe (Rowell, 2014).

Further, fertilisers namely kelp and manure were assessed for micro- and macronutrient content and moisture content. For this 10 x 10 g sub samples were taken of each the kelp and manure. A composite sample was then air dried until a constant weight was reached, with the weights used to calculate the moisture content of the sample. The dried samples underwent digestion and analysis by ICP-MS. Initially, the samples were added to digestion vessels containing 1 mL of Milli-Q water and 9 mL of 80% nitric acid. Subsequently, a microwave digester (Ethos EZ, Microwave digestion system, Milestone) was used to digest the samples at 120 °C for 15 minutes. Following digestion, the samples were diluted 100-fold with Milli-Q water. The diluted, digested samples were then assessed for their macro and micro nutrient content using an ICP-MS (X-series II, Thermo Fisher) (Velitchkova et al., 2013). Further the dried samples were analysed for their carbon, hydrogen, nitrogen and sulphur content ratio using a ThermoScientific CHNS Organic Elemental Analyser. Prior to analysis, all samples were ground using a pestle and mortar and sieved through a 1 mm sieve. Using a microbalance (Mettler Toledo XP6), approximately 2-3 mg of sample was transferred into an aluminium tin foil capsule and folded to close the cups using metal forceps, prior to analysis.

To assess plant growth above and below ground biomass was separated and washed by hand to remove soil. The above and below ground biomass then had their masses determined prior to drying in the oven at 60°C until a constant weight was reached and then weighed again, providing results for the fresh and dry weight of the plants.

A hand-held cone penetrometer with a pressure gauge was used as a method to assess soil compaction, through the resistance of the soil to downward pressure (Beckett et al., 2018; Motavalli et al., 2003), in site assessments conducted prior to the commencement of this PhD (see section 9.2). Measurements were taken along a transect, which ran perpendicular to the Lazybeds. Specifically, Penetration resistance was measured using a 06.01 Eijkelkamp penetrometer (Eijkelkamp Soil & Water, The Netherlands). Measurements were recorded when a uniform pressure allowed cone penetration (base area 3.3 cm2) at a constant rate of 2 cm s^{-1}.

Vegetation surveys of the grassland community at the historic Lazybed site at Harris, Ilse of Rum, were conducted in October 2018. This involved a walk over survey of the site, covering areas both inside and outside the exclosure along three transects. In this survey the presence and extent of the main plant species were assessed in line with the DAFOR (dominant, abundant, frequent, often, rare) scale (Nature Scot, 2024).

3.2.3 Statistical Analysis

All data were statistically analysed using SPSS. One way ANOVA with Tukey's multiple comparison post hoc tests were conducted to test for effects of fertiliser treatments on soil properties and crop yields; p values < 0.05 were deemed significant. It was assumed that all data entered into ANOVA was normally distributed: prior to running the ANOVA analyses data were checked for normality using a visual assessment of QQ plots and Shapiro-Wilk test of the statistical significance of normal distribution. It was also assumed that the distributions had the same variance, and that the data were independent. In Experiment 3.3 and 3.4 the relationship between fertiliser application and plant growth was assessed with simple linear (Experiment 3.3)/non-linear (Experiment 3.4) regression models (depending on the relationship between the two variables) with a level of significance of p =

0.05, using SPSS. In this analysis, R^2 values were used to show effects size that indicate the relationship between the variables input into the model (Cohen, 1977).

3.3 Experiment 3.1: How Kelp and Dung Fertilisers Affected the Growth of Potatoes in Recultivated Lazybeds on the Isle of Rum

Methods

Fields site conditions

The landscape of Rum is scarified with significant areas of historic Lazybed formations, particularly in areas adjacent to historic settlements, making it a suitable location to investigate recultivation (Figure 6). The Isle of Rum is part of the Inner Hebrides, located off the west coast of Scotland, UK (Figure 6). Rum has been designated a National Nature Reserve (NNR), Special Protection Area (SPA), Special Area of Conservation (SAC), Site of Special Scientific Interest (SSSI) due to important flora and fauna populations and geological features. Rum has a northern maritime climate: cool (mean daily highs of 16 ^{o}C in July and August), wet summers and cool (mean daily highs of 6 ^{o}C in December, January and February), wet winters. Substantial rainfall totals are recorded throughout the year (1800 mm pa average in coastal zones), with highest levels experienced in November, December and January (Clutton-Brock and Ball, 1987), whereas May and June are the driest months. However, due to topographical effects there are significant differences in precipitation patterns across the island.

Harris is a historic settlement on the southwest coast of the Isle of Rum, Scotland, UK (56.978576, -6.3744783)) (Figure 6). In 2016, an area (referred to as the exclosure) (20 x 30 m) of historically cultivated Lazybeds (n= 11 Lazybed ridge formations) was fenced to protect experiments from grazing animals (Figure 6, Figure 7, Figure 8). Since 1826 (see section 2.3), the Lazybeds around Harris have been uncultivated and become established by grasses and forbs with grazing by deer, feral goats, a small herd of Highland cattle and Rum ponies (SNH, 2018).

Figure 6 Satellite images of the Isle of Rum, Harris and the field site on the SW coast (56.978633, -6.374936) (Bing Maps, 2023, Google Earth 2023).

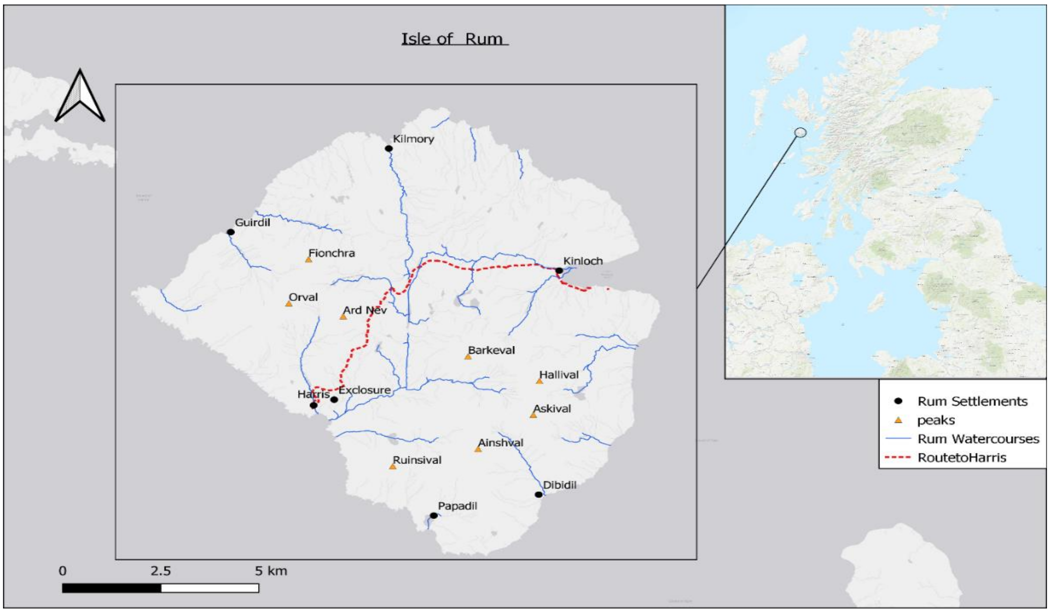

Figure 7 Map of Rum with an insert map of Scotland (ESRI, 2023, Bing Maps 2023). It should be noted that Kinloch is the only currently inhabited settlement.

Figure 8 The deer/cattle-proof exclosure (20 m x 30 m) constructed at Harris, Isle of Rum on Lazybed formations, in 2016, pre-cultivations. Specific permissions were obtained from the landowner Nature Scot, formerly Scottish Natural Heritage, and the site was selected to avoid ancient, listed structures and Natura 2000 sites. This is the dedicated research site, where field experiments were conducted over successive growing seasons.

The Harris settlement where the research fieldsite is located, is significantly drier with yearly rainfall totals averaging 1400 mm, in comparison to the 2740 mm falling at Kinloch, and over 3000 mm in the Rum Cuillin hills. It should be noted that 1400 mm rainfall p.a. is a comparatively high level for the UK. Droughts, however, are not uncommon. In Spring 2019, the Scottish Environmental Protection Agency issued a moderate water scarcity warning after a below average precipitation over the preceding quarterly period. Temperatures on Rum are typically milder than other locations on the same latitude, as a result of the oceanic influence and the position of the Gulf Stream. Frosts occur throughout the year but are most common from October to May with around one hundred days of frost recorded each year at Kinloch. Lying at 57° N, affords Rum long daylight hours in the summer, with only 4 hours of darkness at midsummer. Rum also experiences higher than average sunshine totals with an annual average of 1450 hours.

The geology of Rum is extremely varied. At the Harris research site, the underlying geology is mainly composed of peridotite and allivalite; igneous rocks formed around 60 million years ago during a period of high volcanic activity. These rocks are some of the most ultrabasic in the UK, with high concentrations of magnesium and iron compounds. The soils formed on these ultrabasic rocks at the research site are characterised as peaty gleyed podsols, however, closer to the coast brown earths have developed. Weathering of the underlying geology has enriched these peaty gleyed podsols with high concentrations of magnesium, iron, chromium, cobalt and nickel (Worrell, 2001). Many of these compounds are plant micronutrients which promote growth; however, these soils are low in plant macronutrients (nitrogen, potassium and phosphorous), which severely limit plant growth. Clay particles derived from the underlying geology, further increase the risk of waterlogging in soils. Radiocarbon dating has shown that the Isle of Rum has been in agricultural production dating back to the Neolithic period circa 5000 BC (Canmore, 2018), when vast swathes of the Boreal Forest in Western Scotland were cleared to cultivate crops and graze livestock (Worrell, 1996).

Soil samples from the aforementioned exclosure were collected on an initial trip to Rum in October 2018, to characterise the field site to allow for an evaluation into baseline changes in soil properties. For this experiment, new areas of Lazybeds were turned over (Figure 9B, a process described in historical accounts where the Lazybeds are dug with a footplough to invert and stack clods of turf to create the ridge and furrow formation) and used four fertiliser treatments (fresh kelp, composted kelp+dung, composted dung and no additions–control) in a Latin square design with four replicated plots (Table 1). In total there were sixteen treatment plots each measuring 1.5 m x 0.75 m each planted with four tubers, in an offset formation, with drainage furrows on either side. Kelp was collected from the Rum shoreline (Figure 10). Initial plans were to use kelp stored in middens over winter, to create a composted kelp treatment, however the middens lost their structure and fresh kelp collected in the spring had to be used for this treatment (Figure 11). In addition, resources of dung were collected from the land proximate to the exclosure and were predominantly equine derived. Arran Pilot potatoes were grown, a high yielding early traditional variety, which was found to be a viable crop at the Harris research site in a pilot study (Appendix 1) prior to the commencement of this PhD project. Application of the fertiliser treatments, by volumetric over gravimetric methods, was chosen as it is probable that historically fertiliser application strategies would have been similar due the labour involved and an absence of weighing apparatus (Dodgshon, 1993). Specifically, 10 L of fresh kelp, 5 L of composted manure and 5 L of a composted kelp and manure mix, were applied, as through the composting process it was estimated that approximately 50% of the volume had been lost. This standardised the amount of work involved for each treatment. This was supported by nutrient analysis of the kelp and dung fertilisers once back in the lab, which confirmed that the different fertiliser treatments applied contained approximately the same amount of N. Due to the sensitivities of the site and permissions process relating to the protected statuses of Rum (SNH, 2018), synthetic N was not used as a comparison in this experiment. It is likely that synthetic N would have enhanced crop productivity in the low nutrient status soils at the Harris field site, however, the aim of this experiment was to investigate aspects of historic Lazybed production. Furthermore, it is well established in the literature that applications of synthetic N although supporting food production, reduce the sustainability of the system (Ladha et al., 2022). Due to the time constraints for fieldwork, the decision was taken to not conduct soil fauna surveys on Rum during Experiment 3.1. However, previous work by (Butt & Nuutinen, 2021), had already assessed earthworm populations at the field research site and across Rum. Plans had been made to survey soil fauna and take soil samples for microbial analysis on Rum in further experiments, however, due to the COVID-19 pandemic it was not possible to conduct further field experimentation on Rum.

A

B

Figure 9 (A) Areas of freshly turned over Lazybeds in the autumn, in preparation for spring planting, within the fenced exclosure, at Harris, Isle of Rum and (B) turning over of historic Lazybeds, at Harris, Isle of Rum, to prepare the ground for cultivation.

Figure 10 The Rum shoreline, at Harris, from where kelp was collected. This photo illustrates the challenging environment where kelp is collected. Ruinsival (528 m) can be seen in the background.

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Figure 11 Middens of kelp within the Harris exclosure during the autumn. By the spring the midden had rotted away, and fresh kelp had to be collected for experimental purposes.

Table 1 The field layout for the 2019 growing season Experiment (3.1) at Harris.

Bed A	**Bed B**	**Bed C**	**Bed D**
Control	Kelp	Kelp + Dung	Dung
Kelp + Dung	Dung	Kelp	Control
Dung	Kelp + Dung	Control	Kelp
Kelp	Control	Dung	Kelp + Dung

Results

There were clear differences in potato yields due to the application of kelp and dung fertilisers ($p < 0.0001$) (Figure 12). Fresh kelp fertiliser was found to increase crop yields nine times above yields in the control (no fertiliser) treatment. There was no significant difference in potato yields between dung, kelp+dung and the control treatments. The total number of tubers produced was far greater under kelp fertiliser treatment, with more than double the number of tubers than for the control, dung or kelp + dung fertiliser treatments (Figure 13).

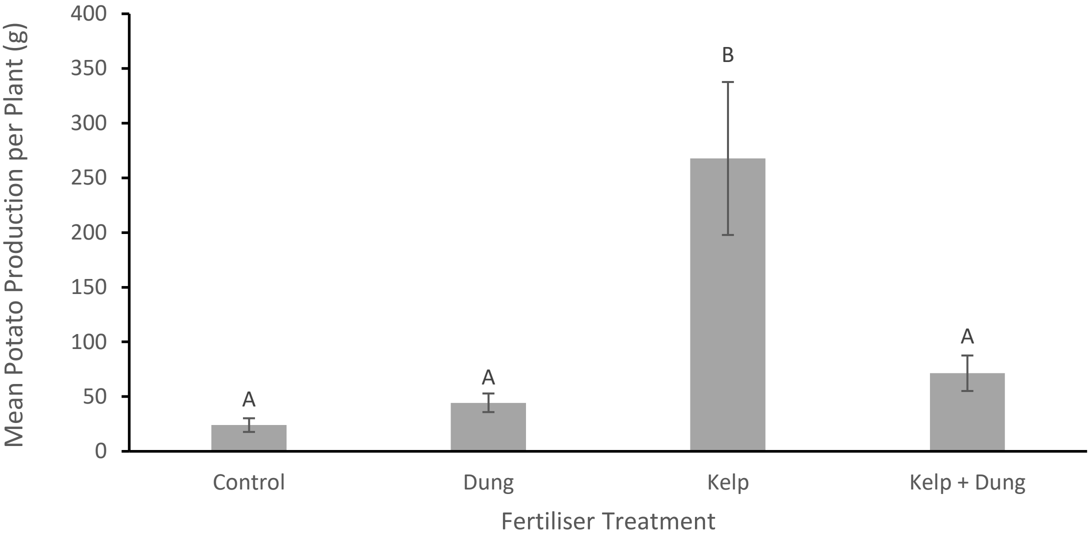


Figure 12 Effects of kelp and dung fertilisers on mean Arran Pilot tuber production (g) per plant in Lazybeds (Experiment 3.1) (Harris, Isle of Rum). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 64, 4 replicates, 4 treatments, 4 potato plants per plots. Error bars represent standard deviation.

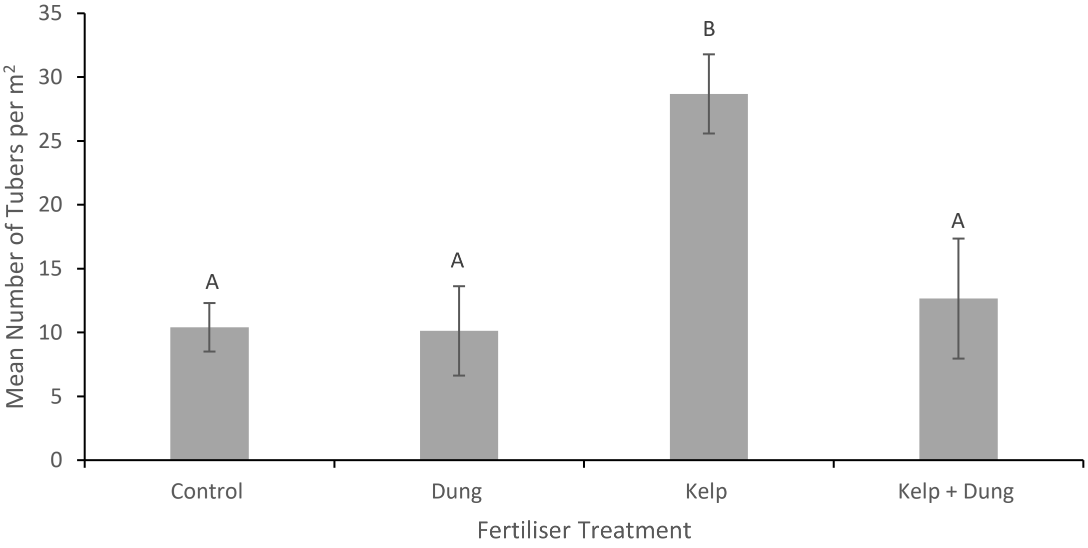


Figure 13 Effects of kelp and dung fertilisers on the mean number of Arran Pilot tubers produced per m2 for the in Lazybeds (Experiment 3.1) (Harris, Isle of Rum). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 64 potato plants, 4 replicates, 4 treatments, 4 potato plants per plot. Error bars represent standard deviation.

There is a strong treatment effect dung + kelp significantly higher for all measures C:N total C and total N $p < 0.001$. However, singular additions of kelp or dung resulted in similar increases in C:N. (Figure 14).

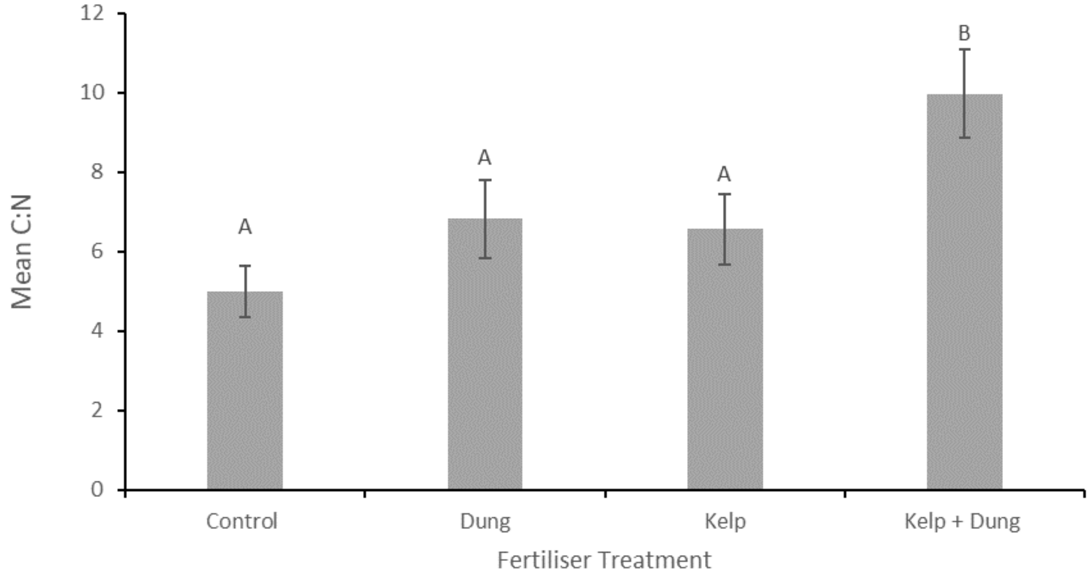


Figure 14 Effects of kelp and dung fertiliser treatments on the mean C:N ratio of the soil in Lazybeds (Experiment 3.1) (Harris, Isle of Rum). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 16, 4 replicates, 4 treatment plots. Error bars represent standard deviation.

Fertiliser treatment significantly affected pH with a p value of 0.04 (*Figure 15*). Kelp, dung, and kelp+dung increased pH above the control treatment. Kelp additions increased pH to a greater extent than dung, mixed kelp and dung additions had the second greatest effect on pH. The variation in the pH values across the replicates was low (it is important to remember that pH is measured on a logarithmic scale). There was no significant difference in soil moisture content between the fertiliser treatments ($p > 0.05$). LOI was significantly affected by fertiliser treatment ($p < 0.01$) with the mixed kelp+dung fertiliser nearly doubling the LOI from the control (*Figure 16*). Dung fertiliser treatment had the second largest effect on the LOI value of the soil samples.

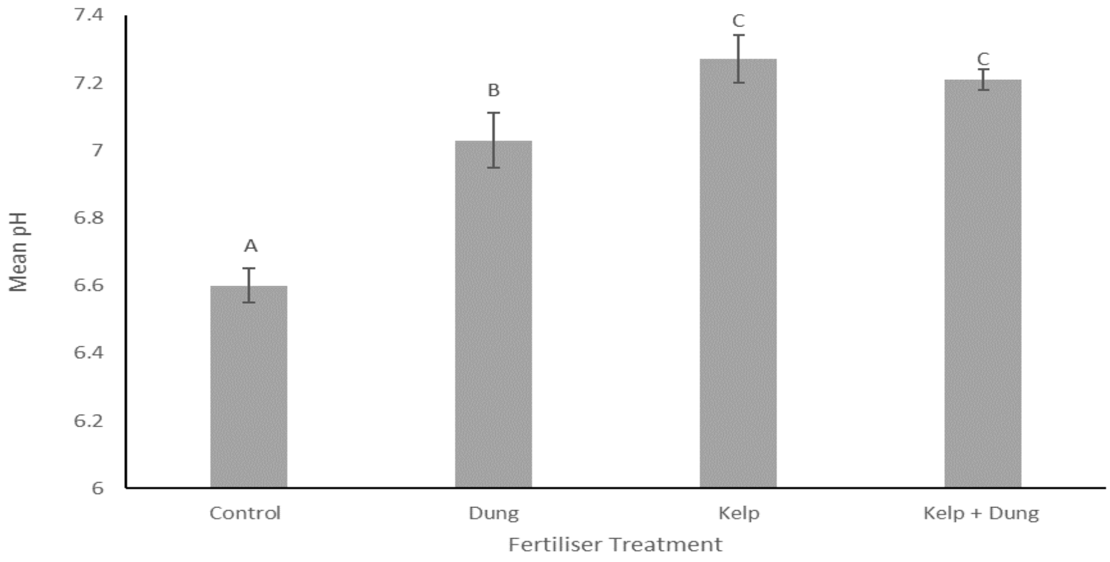


Figure 15 Effects of kelp and dung fertiliser treatments on the mean pH of the soil in Lazybeds (Experiment 3.1) (Harris, Isle of Rum). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 16, 4 replicates, 4 treatment plots. Error bars represent standard deviation.

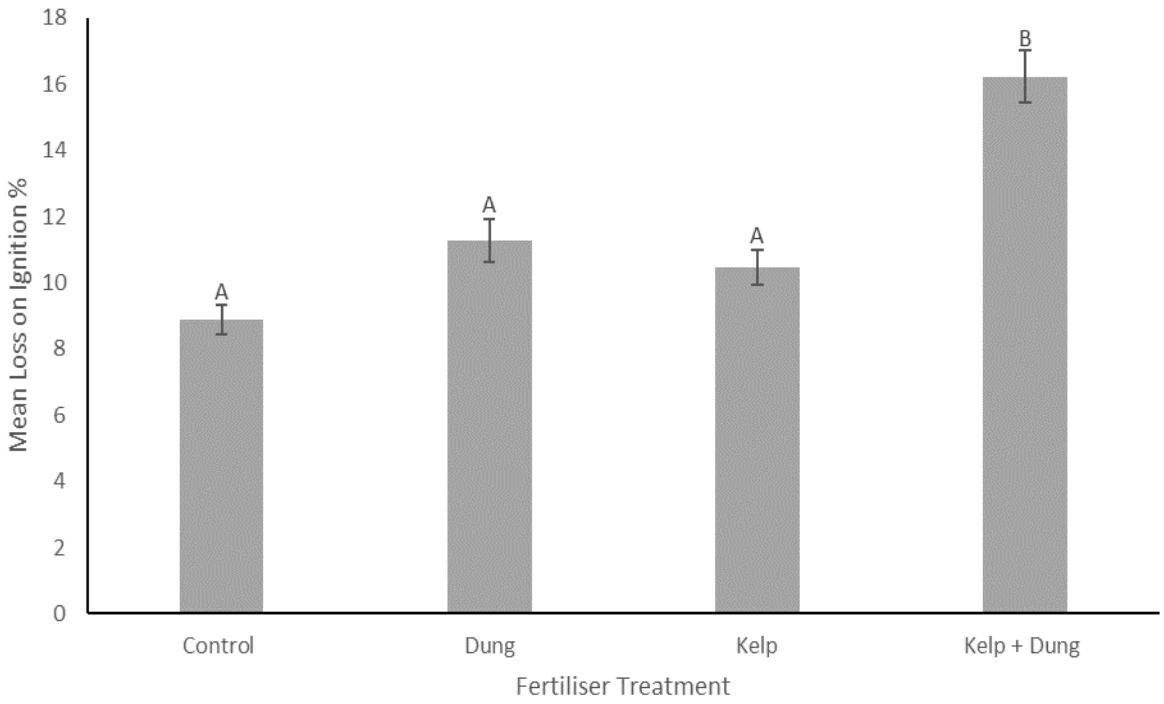


Figure 16 Effects of kelp and dung fertiliser treatments on the mean LOI of the soil in Lazybeds (Experiment 3.1) (Harris, Isle of Rum). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 16, 4 replicates, 4 treatment plots. Error bars represent standard deviation.

Discussion

The results of this study provide insights into the effects of kelp and dung fertilisers on potato yields, tuber production, soil properties, and soil organic matter content. These findings contribute to the existing scientific literature on the impact of seaweed-based and organic fertilisers on crop performance and soil characteristics (Ali et al., 2021; Cai et al., 2019; Hernández-Herrera et al., 2018).

The significant differences in potato yields attributed to the application of kelp fertiliser underscores the efficacy of these amendments in influencing crop productivity. This finding aligns with previous studies highlighting the positive effects of kelp-derived bioactive compounds on plant growth and yield enhancement (Arthur et al., 2007; Ghaderiardakani et al., 2019).

The lack of a significant difference in potato yields between dung, kelp+dung, and the control treatments suggests that, individually, dung did not have an impact on potato yield in this experimental context. This result is consistent with the notion that the effectiveness of organic fertilisers may vary based on soil conditions, microbial activity, and the specific needs of the crop (Garmendia et al., 2018; Lau et al., 2022). However, these results contrast with conventional understanding that dung does stimulate crop growth (Blair et al., 2006; Bulluck et al., 2002). Animal dung, a rich source of organic matter, plays a crucial role in stimulating crop growth through its diverse nutrient content and soil-enhancing properties (Cai et al., 2019). As the dung decomposes, it releases essential nutrients such as nitrogen, phosphorus, and potassium, which are vital for plant development. The organic matter in dung also improves soil structure, increasing its water-holding capacity and promoting aeration, crucial factors for optimal root growth. Studies have shown that the application of animal dung to agricultural fields positively influences soil microbial activity, fostering a nutrient cycling process that further enhances nutrient availability to plants (Ma et al., 2020). Additionally, the presence of beneficial microorganisms in dung, such as mycorrhizal fungi, can form symbiotic relationships with plant roots, facilitating nutrient uptake and overall plant health (Bonfante & Anca, 2009). As such, it is unclear as to why the animal dung and dung-composted kelp fertiliser treatments did not have comparable effects of stimulating crop growth to fresh kelp, as analysis of the nitrogen content of the fertilisers confirmed that the different fertilisers had been added at rates which standardised total N additions. Although not measured in this study, differences may be due to the form of nitrogen or due to the presence of plant growth hormones, of which kelp is known to be a rich source. The form of nitrogen in animal manures can significantly impact plant growth due to variations in its availability and conversion processes within the soil (Ahmed et al., 2022). Nitrogen in animal manures exists in different forms, primarily as organic nitrogen and ammonium nitrogen, as well as nitrate nitrogen to a lesser extent. The balance between these forms of nitrogen and their transformations in the soil is crucial for optimising plant growth. Proper management practices, including appropriate timing and application methods, can enhance the efficiency of nitrogen utilisation by crops, minimise nutrient losses, and promote sustainable agricultural practices.

The increase in the total number of tubers produced under the kelp fertiliser treatment, more than double that of the control, dung, or kelp + dung fertiliser treatments, emphasises the efficacy of kelp in promoting tuber development. This finding provides evidence for the role of kelp-derived compounds in enhancing nutrient uptake and fostering optimal conditions for tuber formation (Asad et al., 2017; Zotarelli et al., 2015).

The treatment effect observed in dung + kelp, is greater for measures such as C:N, total C, and total N with $p < 0.001$, suggests a synergy between dung and kelp. The combined effect of these amendments appears to have a more pronounced impact on soil carbon-to-nitrogen ratio and total N compared to singular additions of kelp or dung. This aligns with the hypotheses presented earlier in this thesis predicting the potential benefits of combining organic (manure) and seaweed-based fertilisers for enhanced crop growth through improvements to soil fertility. Research by Zaman et al. (2015), also indicates that positive effects on plant growth can be achieved by combining plant growth hormones and a source of N. Specifically, the combination of gibberellins with a nitrogen-based fertiliser can lead to substantial increases in crop growth. This effect was observed in a variety of crops, including forage crops and can enhance growth in low temperatures. Additionally, there is scope to increase yield by incorporating an auxin or cytokinin along with a nitrogen-based fertiliser (Zaman et al., 2015). However, further research into the applications of these products to achieve efficiencies in yield in needed.

The significant impact of fertiliser treatment on soil pH (p = 0.04) is noteworthy, with kelp, dung, and kelp+dung increasing pH above the control treatment. Kelp additions exhibited a greater influence on pH compared to dung, while mixed kelp and dung additions had the second greatest effect. These changes in soil pH could influence nutrient availability and microbial activity, impacting overall soil health.

Soil moisture content did not show significant differences between fertiliser treatments (p > 0.05), indicating that the observed effects on crop yields and soil properties were not associated with variations in soil moisture. This contrasts with other studies that have found that different fertiliser sources affect soil moisture retention (Bulluck et al., 2002; Marinari et al., 2000). These differences are likely explained by the relatively short timeframe of the experiment with likely effects of fertiliser type on soil moisture retention accumulating over time and the severely dry conditions (as indicated by 3-month cumulative drought indices) the field site was under at harvest (CEH, 2024).

The significant effect of fertiliser treatment on the LOI values, with the mixed kelp+dung fertiliser nearly doubling the LOI compared to the control, suggests an increase in organic matter content. Dung fertiliser treatments had the second-largest effect on the LOI value, indicating their contribution to soil organic matter. This aligns with existing research which has found that different fertiliser types result in changes to soil carbon. Specifically, soil organic carbon increases under long term application of dung/manure derived organic fertilisers (Mayer et al., 2022). Further, the level of soil organic carbon of which LOI is used in this study as an indicator measure in soil is an important factor to determine the overall sustainability of the agroecosystem (Schreefel et al., 2022). OM in soils acts as a sponge to hold water and increase the soils cation exchange capacity (Costantini et al., 2018; Quastel & Webley, 1947). Cation exchange capacity is a property of soils which retains cations such as potassium, magnesium, calcium, and ammonium, increasing the soils nutrient status. Through binding these positively charged cations to the negatively charged particles in the OM, reducing the levels of nutrients lost from the soil through water transport (Bulluck et al., 2002). Further, as OM decomposes, it releases the nutrients bound at cation exchange sites and nutrients in the body of the OM (Dhaliwal et al., 2019). The rate of OM decomposition is determined by a range of biotic and abiotic factors, such as action of soil mesofauna and temperature (Dynarski et al., 2020; Filser et al., 2016). Excess nutrients applied to land in the form of inorganic fertilisers rapidly increase the rate of OM decomposition. However, under most circumstances the rate of organic matter decomposition in temperate climates is at a supressed rate, which allows for the steady release of nutrients throughout the growing season, ensuring that the plant community has access to the nutrients it needs for healthy growth and reproduction.

The changes in measured soil properties and yields did not correlate as hypothesised, and as expected from a review of existing literature. This warrants further investigation to disentangle the mechanisms driving increases in yields with the use of fresh kelp fertilisers. Previous research suggests that the presence of plant growth hormones, which were not measured in this study, could play a significant role in driving these increases (Rocha et al., 2020; Zaman et al., 2015; Zheng et al., 2016). Specifically, kelp contains a variety of bioactive compounds such as alginate, tannins, and plant growth hormones, which promote plant growth. It is proposed the presence of these bioactive compounds coupled with the nutrient content of the kelp result in high yields when it is used as a soil amendment.

3.4 Experiment 3.2: Extended Kelp and Dung Fertiliser Trials, Anglesey 2020

Methods

A second year of the kelp+dung fertiliser trial was relocated to Anglesey, due to COVID-19 restrictions, where an extended range of kelp- and dung-derived fertilisers were tested. The crop was grown on a previously uncultivated area of grassland which had been managed through regular cutting in the summer (53.273744, -4.2727464). The vegetation at the site comprised primarily of *Lolium perenne*, *Taraxacum sp*., *Ranunculus repens* and *Bellis perennis*. The soil at the site was slowly permeable, seasonally wet, acidic, loamy and clayey (Landis.org.uk). Climatically, Anglesey is drier, warmer and receives more sunshine than the neighbouring mainland and the Isle of Rum. Lazybeds were dug by hand into the grass sward, using techniques (to cut, turnover and stack clods of turf in the desired Lazybed formation, with a wider than conventional ridge structure) described in historical accounts of Lazybed systems in Scotland (Darling, 1945). In March 2020, four Lazybeds were marked out, with each measuring approximately 1.5 m x 9 m, split into six treatment plots for each Lazybed measuring 1.5 m x 1.5 m (Figure 17) (Table 2). Clods of turf were then cut from the edges and piled upon the middle section of each Lazybed bed to create a ridge a furrow system, further detailed in Section 3.3 *methods*. Next the six fertiliser treatments, replicated four times, were added to treatment plots. In autumn prior to this experiment, kelp that had been dislodged and brought ashore was collected from the Anglesey coastline (53.211430, -4.5016623). The kelp was rinsed in freshwater, then placed in a plastic trug with drainage holes and stored outside for 5 months (Figure 18). This provided the decomposed kelp treatment, with fresh kelp treatment being collected from the same location the day prior to planting. Two fertiliser treatments tested in this experiment were commercially available: 1. Cattle Manure and 2. Seaweed extract liquid fertiliser (Maxicrop, Plant Growth Stimulant, Stermat). Fresh kelp was also mixed with manure to provide another treatment. Fertilisers were added to each treatment plot by volume (Fresh kelp- 15 L watered with 10 L, Composted kelp- 7.5 L watered with 10 L, Fresh kelp and dung – 7.5 L kelp + 5 L dung watered with 10 L, Dung- 10 L watered with 10 L) apart from the seaweed extract liquid fertiliser, which was added in the following dose (5 ml L^{-1} 0.1 m^{-2} of soil= total application of 10 L), however, the manufacturer recommends that this application is repeated every 14 days, however due to covid restrictions imposed shortly after the commencement of the experiment it wasn't possible to revisit to reapply this treatment, likely impacting yields in this experimental treatment. Furthermore, Maxicrop, Plant Growth Stimulant is made from *Ascophyllum nodosum*, which may partly account for observed differences. The volumes were adjusted for expected N and moisture content from a review of literature and based on total N content from the analysis of samples of kelp and dung collected from Rum in 2018 (see Section 3.3 for further details regarding this methodological approach). This is in line with the experimental treatments application rates used in the Rum field trial per m^2. These fertilisers were dug into each Lazybed treatment plot with a 0.3 m buffer zone between neighbouring plots. Four, chitted, Arran Pilot potatoes, the same variety as for Experiment 1, were planted in each treatment plot, the day after the beds were dug (24/3/2020). Due to dry weather conditions experienced at the time of planting and in the first few weeks of growth, the Lazybeds were watered on three occasions (Figure 19). After 15 weeks (10/7/2020), the potatoes were harvested, washed dried and weighed, and soil samples were taken by hand using a trowel from each treatment plot (Figure 20).

Table 2 Design of Experiment 3.2 with treatments and layout used in the Anglesey 2020 field trial.

Bed A	**Bed B**	**Bed C**	**Bed D**
Dung	Composted kelp	Seaweed liquid fertiliser	Control
Seaweed liquid fertiliser	Fresh kelp	Fresh kelp and dung	Dung
Fresh kelp	Fresh kelp and dung	Dung	Seaweed liquid fertiliser
Control	Dung	Composted kelp	Fresh kelp and dung
Composted kelp	Seaweed liquid fertiliser	Control	Fresh kelp
Fresh kelp and dung	Control	Fresh kelp	Composted kelp

Figure 17 The newly constructed Lazybeds prior to planting in the Anglesey field trial, March 2020

Figure 18 The decomposed kelp treatment prior to application.

Figure 19 The potato plants in June 2020, Anglesey.

Figure 20 The harvested crop of potatoes from the Anglesey field trial by treatments in columns. From left to right, kelp+dung, seaweed extract, composted kelp, fresh kelp, dung, no fertiliser controls.

Results

Fertiliser treatment significantly affected potato yields and total number of potatoes produced (Figure 20, Figure 21 and Figure 22). in the 2020 Lazybed Experiment (3.2). Fresh kelp mixed with manure had the second greatest effect, followed by manure and composted kelp which were comparable in their effect on yield. The commercially available seaweed extract did not increase yields above control levels. Composted kelp and manure had intermediate effects on yield, with above that of the control but not to the extent observed in the fresh kelp and fresh kelp + manure treatments.

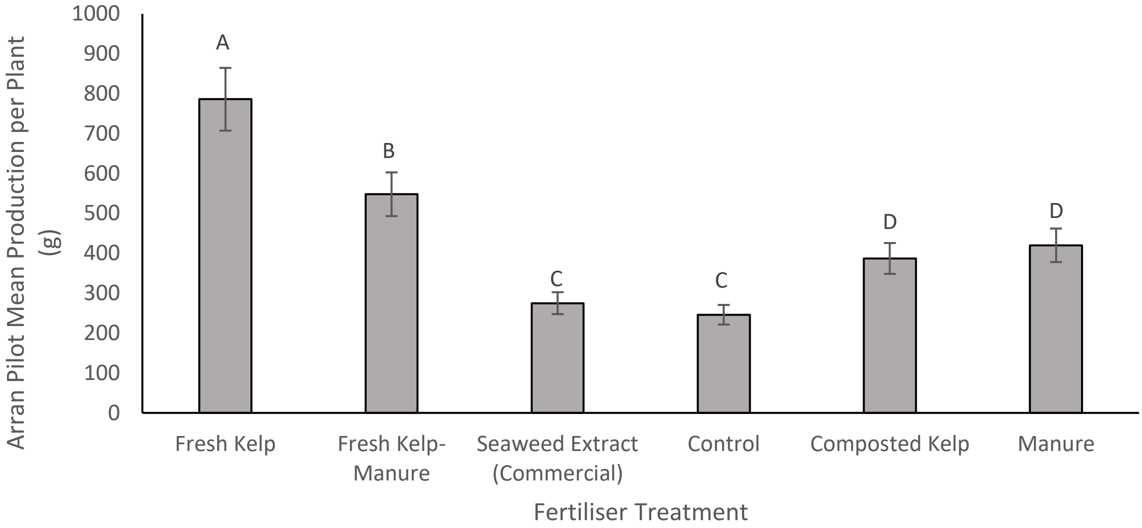


Figure 21 Effects of kelp and dung fertilisers on mean Arran Pilot tuber production (g) per plant in Lazybeds (Experiment 3.2) (Anglesey). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 96, 4 replicates, 6 treatments, 4 potato plants per plots. Error bars represent standard deviation.

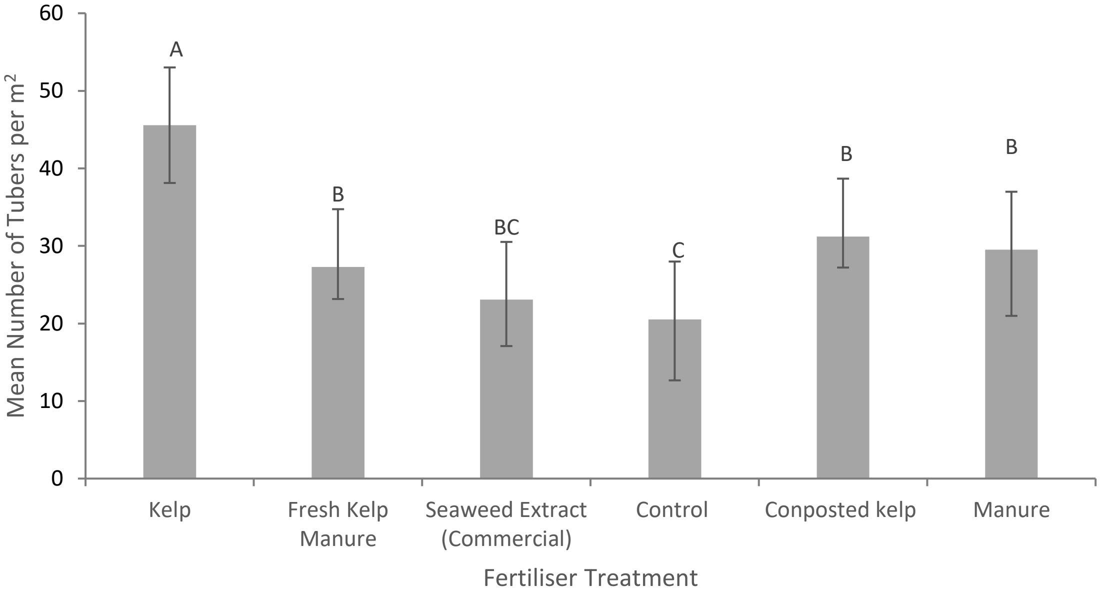


Figure 22 Effects of kelp and dung fertilisers on the mean number of Arran Pilot tubers produced per m2 in Lazybeds (Experiment 3.2) (Anglesey). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 96, 4 replicates, 6 treatments, 4 potato plants per plots. Error bars represent standard deviation.

Discussion

The findings of the 2020 Lazybed experiment reveal a significant impact of fertiliser treatments on potato yields and the total number of potatoes produced. These results contribute to the existing scientific literature and corroborate the findings from Experiment 3.1, on the use of different fertilisers in potato cultivation, shedding light on the efficacy of various kelp-based amendments.

Fresh kelp increases potato yields above that of the other fertilisers trialled in this study. This result aligns with previous studies highlighting the beneficial effects of kelp on crop productivity (Knox et al., 2015). The rich array of bioactive compounds in fresh kelp, including cytokinins, auxins, and trace elements, is known to stimulate plant growth and enhance nutrient uptake, contributing to the increase in potato yields observed in this experiment (Blunden et al., 1997).

The combination of fresh kelp with manure also demonstrated a significant positive effect on potato yields, though not as pronounced as the fresh kelp alone. This synergistic effect suggests that the incorporation of manure complements the nutrient profile of fresh kelp, enhancing its overall impact on potato growth. This finding is consistent with literature emphasising the potential benefits of combining organic amendments to optimise soil fertility and crop yield (Celestina et al., 2019).

Interestingly, commercially available seaweed extract did not exhibit a significant increase in potato yields above control levels. This result contrasts with the performance of fresh kelp, suggesting that the form, application, and processing of seaweed-based fertilisers plays a crucial role in their effectiveness. The variations in extraction methods and concentration of bioactive compounds in commercially available products might explain the observed differences as many of the plant growth hormones are highly labile and likely to be degraded somewhat during the industrial extraction process (Francis & Sorrell, 2001). Furthermore, it is likely that the infield application method used in this experiment for the commercially available seaweed extract, may have resulted in the rapid transport down the soil profile, further exacerbated by the recent disturbance to the soil during the creation of the Lazybed structures, resulting in the observed low yields for this treatment. Moreover, this product was not applied in accordance with the manufacturer's recommendation (which state that repeat applications are required every 14 days). However, due to practicalities and Covid restrictions it was not possible to do this. If the seaweed extract had been applied as recommended it is likely yields would be greater than those observed in the control treatment.

Composted kelp and manure treatments showed intermediate effects on yield, falling between the control and the more potent fresh kelp treatments. This result underscores the importance of the form and state of kelp amendments, as composting may alter the availability of certain bioactive compounds. The comparable effects of manure and composted kelp further highlight the significance of organic matter in enhancing potato yields, through increased water and nutrient holding capacity and soil structure. This has further relevance in conventional intensively cultivated systems where soil structural degradation is common (Grandy et al., 2002), but soil structural degradation is also likely to be present to a lesser degree in lower intensity cultivation systems such as Lazybeds. The use of green and animal, compost/manure soil amendments in intensively cultivated systems has been shown to lead to the recovery of soil organic matter and soil structure, and that this recovery was rapid with persistent effects (Grandy et al., 2002). Further differences have been found in how the source of organic matter affects the stabilisation of small or large soil aggregates. This warrants further investigation as to the stabilising effects of kelp soil amendments and how they compare to traditional soil amendment to confer soil stability and associated soil carbon.

These findings offer potential avenues for agricultural practitioners, wishing to explore alternative soil amendments and lower impact systems whilst maintaining yields. Incorporating fresh kelp or a combination of fresh kelp and manure into fertiliser practices can potentially lead to substantial increases in potato production. However, the limited efficacy of commercially available seaweed extract suggests the need for careful consideration of product selection and pretreatment in optimising fertiliser strategies.

In conclusion, the 2020 Lazybed experiment provides insights into the impact of different kelp-based fertilisers on potato yields. The efficacy of fresh kelp, the synergistic effect of fresh kelp with manure, and the limited efficacy of commercially available seaweed extract highlight the nuanced relationship between fertiliser type and crop response. These results contribute to the ongoing efforts to refine agricultural practices, emphasising the importance of selecting appropriate kelp-based fertilisers for optimising potato production.

3.5 Experiment 3.3: Effects of Kelp Application Rates on Spring Barley Growth

Methods

This experiment utilised an approach to test the rate at which the optimum benefit is derived from the addition of kelp. It was hypothesised, that the relationship between kelp additions and crop productivity display a quadratic functional form (Dhakla et al., 2021), tending to a point where the maximum yield is reached and that by using the gradient method as described by (Kreyling et al., 2018), it would be possible to more accurately determine the fertiliser application rate where the maximum yield is expected. The gradient method does not employ replicates in its design, instead the resources are used to test a greater number of treatment levels, here the kelp application rates.

Kelp which had been washed up on the beach, was collected from the Anglesey coastline (53.211430, -4.5016623), on the 10/01/20. The kelp was stored outside for 9 days in plastic trugs with holes drilled for drainage of rainwater. The kelp was transported to the laboratory on the 20/01/20, after the holdfasts and stipes were removed, leaving the blades, which were washed by submerging in 5 L of tap water and further rinsing in tap water using a hosepipe (20 L over 2 minutes) to remove residues and debris. Once in the laboratory (21/01/20) the kelp was manually cut into 2 cm^2 pieces. The amount of kelp in each treatment pot was calculated based on 22 incremental application rates of between 0 and 105 kg N ha^{-1} added to the system at sowing (Table 3). A rate of 90 kg N ha^{-1} is recognised as the optimum rate (Teagasc, 2018).

Figure 23 The early (left) and intermediate (right) growth stages of the Spring Barley-kelp application rates experiment (Experiment 3.3).

Table 3 Calculation of the mass of fresh kelp applied based on N content, for use in Experiment 3.3.

N application rate kg N ha^{-1}	Kelp dry (g) mass based on 2.5% N	Fresh mass (g) of kelp to be applied based on average 60% moisture content
105.00	4.66	11.66
100.00	4.44	11.11
95.00	4.22	10.55
90.00	4.00	10.00
85.00	3.77	9.43
80.00	3.55	8.88
75.00	3.33	8.33
70.00	3.11	7.78
65.00	2.88	7.20
60.00	2.66	6.65
55.00	2.44	6.10
50.00	2.22	5.55
45.00	1.99	4.98
40.00	1.77	4.43
35.00	1.55	3.88
30.00	1.33	3.33
25.00	1.11	2.78
20.00	0.88	2.20
15.00	0.66	1.65
10.00	0.44	1.10
5.00	0.22	0.55
0.00	0.00	0.00

Three spring barley seeds (*Hordeum vulgare)* obtained from Cotswold Seeds Ltd. were planted (3 cm deep) in mesocosms (PVCu, 11.5 cm diameter pipe, cut to 15 cm lengths, sealed at one end using 2 mm mesh cut to squares and affixed using duct tape) (Figure 23). The growing media used consisted of a 1 cm base gravel layer to promote drainage, a 9 cm layer of John Innes no.1 potting compost, then a further 5 cm layer which contained the specified level of kelp for the treatment mixed with the aforementioned compost. In field settings, the kelp would be incorporated further into the soil profile, but 5 cm was chosen in this experiment to standardise the process; this depth was also deemed proportional to the small size of the mesocosms (with kelp being incorporated into the top third of the mesocosm). John Innes composts are extensively used in research, with the no.1 standard used in this experiment as this compost has the lowest nitrogen, phosphorus and potassium contents of the three standard compost available (Bunt, 1963). This was to try and replicate the growing conditions in marginal soils such as the Isle of Rum, where nutrient levels are low, however, significant differences in key soil properties persist between Rum soil and John Innes compost. Macronutrient contents for John Innes no.1 are as follows N 5.1%, P 3.2% and K 8.1%) (Bunt, 1963), these are comparable with medium-low soil nutrient contents (PDA, 2024), but due to the small size of the pots used in experiments coupled with watering regimes, it is likely that these nutrients are rapidly lost, leaving the compost in a low nutrient state. The mesocosms were initially given 100 ml of water on the 21/3/20, however, this was reduced to 75 ml two days later and thereafter they were watered with 75 ml twice weekly. On the 30/1/20, weaker seedlings were removed leaving the strongest single seedling in each mesocosm.

Results

Regression analysis found that kelp application rates were a significant factor explaining the variance in above ground biomass ($p < 0.05$) and below ground biomass ($p < 0.05$), with R^2 values of 0.58 and 0.65 respectively, meaning that the model explains 58% of the variance in above ground biomass and 65% of the variance in below ground biomass for spring barley under the different levels of kelp fertiliser treatments (*Figure 24, Figure 25*). For below ground biomass the line of best fit has a steeper gradient, therefore the effect on the growth of below ground biomass is greater than above.

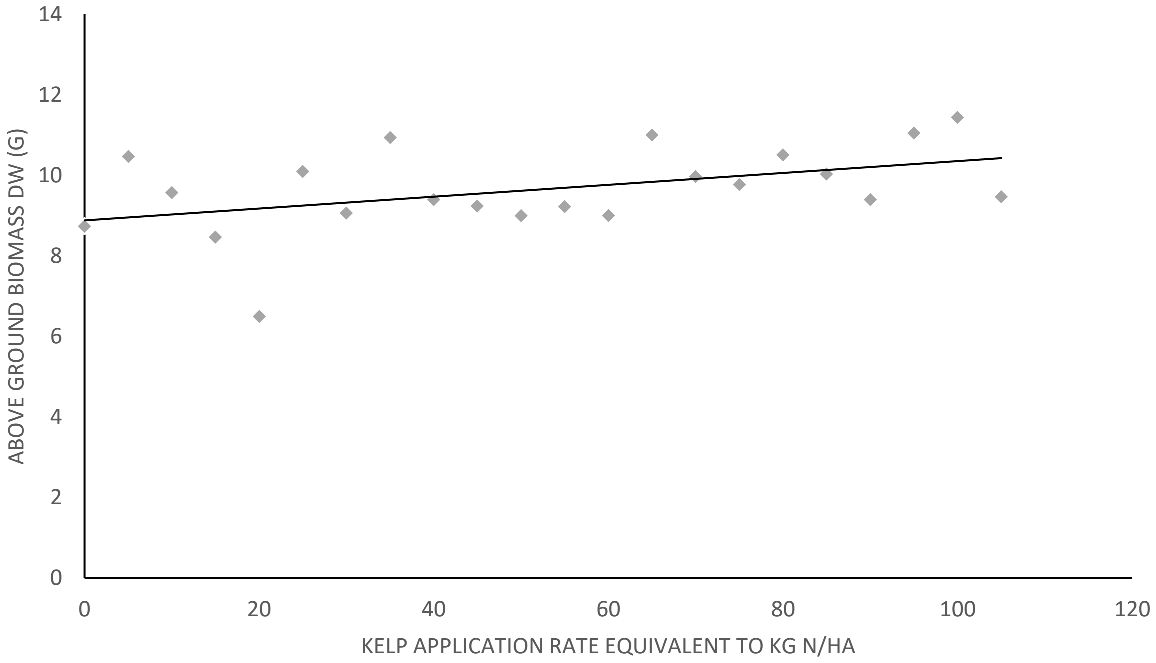


Figure 24 Effects of kelp fertiliser application rate on the above ground biomass of Spring Barley (Hordeum vulgare) (Experiment 3.3) (Myerscough Glasshouse). N= 22 mesocosms.

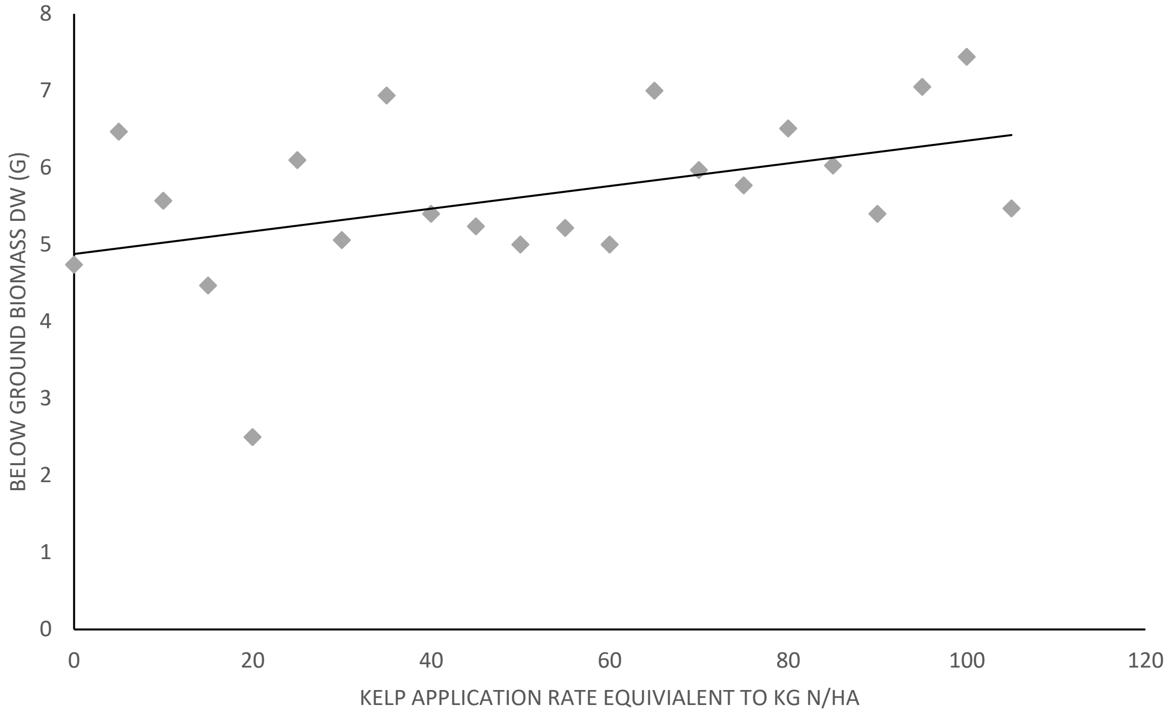


Figure 25 Effects of kelp fertiliser application rate on the below ground biomass of Spring Barley (Hordeum vulgare) (Experiment 3.3) (Myerscough Glasshouse). N= 22 mesocosms.

Discussion

The results of the regression analysis provide information into the relationship between kelp application rates and the biomass of spring barley, shedding light on the significant factors influencing both above ground and below ground biomass. The findings contribute to the existing scientific literature on the use of seaweed-based fertilisers in agriculture, offering further quantitative evidence of the impact of kelp application on crop growth (Cole et al., 2016). However, this research differs significantly from most research into seaweed-based fertilisers which focus on extracts and composts rather than the raw resource (fresh kelp) as investigated in this experiment.

The observed statistical significance of kelp application rates in explaining the variance in above ground and below ground biomass underscores the importance of considering the dosage of kelp fertiliser in influencing spring barley productivity. To increase the economic and environmentally sustainability of agricultural practices it is important to determine the most cost-efficient application rate, although sometimes this will differ from the maximum effective application rate (Timilsena et al., 2015). However, seed pretreatments containing biostimulants can be used to further enhance yields once the maximum effective application rate is reached (Abd El Hamid & Bugaev, 2020; Shitikova & Lammas, 2022).

The R^2 values of 0.58 for above ground biomass and 0.65 for below ground biomass suggest that the regression models explain a substantial proportion of the variability in the respective biomass measures. This implies that 58% and 65% of the variance in above ground and below ground biomass, respectively, can be attributed to the variations in kelp application rates. These R^2 values highlight the influence of kelp fertilisers on spring barley growth. The remaining variation may be explained by genetic differences, as other abiotic factors were controlled.

The graphical representation of the regression models (Figures 25 and 26) reinforces the observed relationships. The steeper gradient of the line of best fit for below ground biomass indicates a more pronounced effect on below ground growth compared to above ground biomass. This suggests that the dosage of kelp fertiliser has a greater impact on the development of roots, potentially influencing nutrient uptake and plant growth.

These findings align with previous studies on seaweed-based fertilisers, which have highlighted the positive effects of seaweed extracts on plant growth and development. The bioactive compounds present in kelp, such as auxins, cytokinins, and trace elements, are known to stimulate root development and nutrient absorption (Procházka et al., 2015). The current study contributes quantitative evidence to this body of knowledge, emphasising the application rate dependent nature of the relationship between kelp application rates, based off N requirements and spring barley biomass.

The impact of kelp application on plant growth mirrors studies looking at the initial growth response observed with synthetic N (Teagasc, 2018). Notably, growth responses in this experiment extended beyond the recommended N application rate, although the experiment's early cessation hinders definitive conclusions. The continued growth, surpassing the recommended N application rate of 90 kg N ha^{-1}, may be attributed to various factors, including the influence of plant growth hormones or the activation of the soil microbial community through priming (Arthur et al., 2007). Nonetheless, further investigation is essential for a comprehensive understanding of these dynamics.

In conclusion, the regression analysis provides evidence of the influence of kelp application rates on spring barley biomass. The results contribute to the existing scientific literature, emphasising the application rate dependent nature of the relationship and providing quantitative evidence for the effective utilisation of seaweed-based fertilisers in agriculture.

3.6 Experiment 3.4: Effects of Kelp Fertiliser Application Rate on the Growth of Lettuce

Methods

This experiment (set up in June 2020) used a combined methodological approach with a small number of replicates (3) per-treatment, with a gradient design (as used in Experiment 3.3) (Kreyling et al., 2018). Kelp collected fresh from the Anglesey shoreline and processed as detailed earlier in this chapter, had application rates between 0-60 kg N ha $^{-1}$, with 10 kg N ha $^{-1}$ increments The base level of N present in the John Innes composts modified the total N content of mesocosm, however this was at a consistent value across all treatments, and this experiment sought to determine effects on the application rate of kelp by N content as opposed to total N in the system. It has been determined that at 5% N concentration in the mesocosms equates to a nutrient stock of ~4 kg N ha^{-1}. Lettuce seeds were grown in mesocoms and conditions as detailed in section 3.5 *methods*.

Three lettuce seeds were planted in each mesocosm, with weaker seedlings removed after 1 week, leaving, one lettuce seedling per mesocosm. Further, although historical accounts do not describe Lazybeds being used to grow lettuce, lettuce is now commonly grown across Scotland where conditions permit, with communities encouraged to grow their own as part of sustainability efforts (Sustainable Uist, 2012). In addition, lettuce was chosen due to its rapid growth thereby shortening the experiment. The mesocosms were kept outside in ambient conditions, summer NW England, for the duration of the experiment, and watered as required to maintain soil moisture. After 10 weeks the experiment was harvested.

Results

As kelp application rates increased, the fresh mass of lettuce also increased (*Figure 26*). However, the initial applications of kelp equivalent to 10 kg N ha^{-1} and 20 kg N ha $^{-1}$, did not increase lettuce growth. The largest difference between two consecutive treatments was from the increase from 40 kg N ha^{-1} to 50 kg N ha $^{-1}$.

Regression analysis found that kelp application rates were a significant factor explaining the variance in lettuce fresh mass ($p < 0.05$) with an R^2 value of 0.63, meaning that the model explains 63% of the variance in lettuce mass under the different levels of kelp fertiliser treatments. This means that the data is a relatively good fit to the curve (which again can be seen through the error bars).

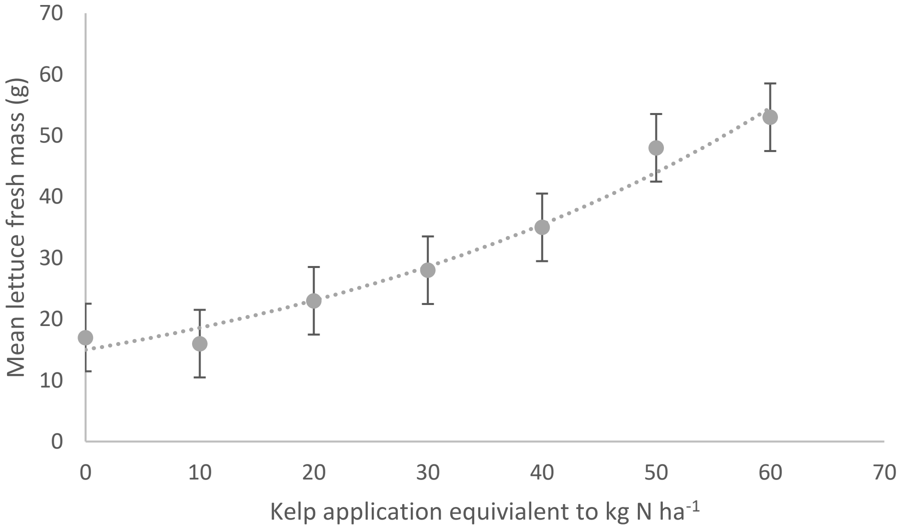


Figure 26 Effects of kelp fertiliser application on the mean mass of lettuce (Experiment 3.4) (Garden Experiment, Preston). n= 21, 3 replicates, 7 treatments. Error bars represent standard deviation.

Discussion

The results of Experiment 3.4 contribute to understanding of the relationship between kelp application rates and lettuce growth, shedding light on the impact of seaweed-derived fertilisers on crop productivity. The observed positive correlation between kelp application rates and the fresh mass of lettuce aligns with previous research emphasising the growth-promoting properties of seaweed extracts (Smith et al., 2018; Brown and Saa, 2015). Although the regression line is not of a particularly steep gradient, even a small increase in yields can be significant in an agricultural business setting. However, the complexity of this relationship is evident from the findings that the initial applications of kelp, equivalent to 10 kg N ha^{-1} and 20 kg N ha $^{-1}$, did not result in a significant increase in lettuce growth.

The lack of a noticeable effect at lower kelp application rates is consistent with the notion that the beneficial impact of seaweed-based fertilisers may be dependent on the application rate (Khan et al., 2009). This observation suggests that there might be a threshold below which the concentration of bioactive compounds and nutrients in the kelp amendments is insufficient to result in a measurable response in lettuce growth. This threshold effect is not uncommon in studies involving organic amendments, where it is also important to determine upper thresholds for the optimal application rates for enhancing benefits without inducing negative effects must be carefully determined (Kumar et al., 2017). The most substantial difference in lettuce growth occurred between 40 kg N ha^{-1} and 50 kg N ha^{-1} kelp application rates. This finding implies that there might be a threshold/critical range of kelp application rates wherein the lettuce crop is particularly responsive to the added nutrients and bioactive compounds. Beyond this range, the marginal increase in growth becomes less pronounced, indicating a possible saturation point or diminishing returns associated with higher kelp application rates. This aligns with similar reported observations regarding the nonlinear relationship between fertiliser application rates and crop yield (Basso et al., 2019). Applications of kelp at a rate equating to 50 kg N ha^{-1} would not be too demanding on natural resources in small scale set ups however this is likely unfeasible at scale (see section 7.3 and 7.4 for further discussion regarding scalability).

The regression analysis further strengthens the evidence for the significance of kelp application rates in explaining the variance in lettuce fresh mass. The high R^2 value of 0.63 suggests a strong relationship between the independent variable (kelp application rate) and the dependent variable (lettuce fresh mass). This finding supports the idea that kelp application rate is a critical factor influencing lettuce growth, reinforcing the need for precision in determining optimal application rates for maximising crop yield.

Experiment 3.4 highlights a relationship between kelp application rates and lettuce growth. While an overall positive correlation was observed, indicating the growth-promoting potential of kelp, the lack of a significant effect at lower application rates and the diminishing returns at higher rates underscore the need for precise kelp applications. These findings contribute to the existing literature on seaweed-based fertilisers, emphasising the importance of understanding the nuanced dynamics involved in optimising their use for sustainable and productive agriculture.

3.7 Experiment 3.5: Effects of Kelp Decomposition on the Growth of Lettuce

Methods

To determine how the level of kelp decomposition impacts crop growth, fresh kelp was added to mesocosms at minus 4 weeks, minus 2 weeks, minus 1 week and on the day of planting, creating four different levels of kelp decompositional stages at the point of sowing. These mesocosms were kept at ~20 °C, inside uncovered in a south facing aspect and watered every 2 days allowing for decompositional processes to occur. Twenty plastic mesocosms (11.5 cm diameter x 15 cm length), secured with 1 mm mesh at one end, with a 1 cm layer of 20 mm gravel to promote drainage, were filled with John Innes no. 1. Each treatment was replicated five times. The kelp fresh at the time of application was incorporated into the compost through mixing by hand into the top 5 cm of each mesocosm. In practice in field settings the incorporation of kelp into the soil profile would typically extend further, but for standardisation purposes, a depth of 5 cm was chosen. This depth was selected considering the relatively small size of the mesocosms, with kelp being integrated into the top third of each mesocosm. The choice of John Innes no.1 compost in this study aligns with its frequent use in research. This particular compost was selected for its lower nitrogen, phosphorus, and potassium contents compared to other available standards, as outlined by Bunt (1963). The experiment aimed to partially emulate growing conditions in marginal soils, such as those found on the Isle of Rum, where nutrient levels are naturally low. The macronutrient contents of John Innes no.1 compost (N 5.1%, P 3.2%, and K 8.1%) are akin to medium-low soil nutrient levels (DEFRA, 2024). However, the small size of the experiment pots and the watering regimes employed result in rapid nutrient loss, leaving the compost in a state of low nutrient availability. After 4 weeks, the mesocosms were transferred to a transparent growth tunnel kept outside in a south facing aspect, with inlets for air circulation. Three lettuce seeds (Salad Bowl) were planted and after 2 weeks the weaker seedlings were removed leaving the strongest seedling in each mesocosm. The lettuce was then left to grow for another 8 weeks (with the watering regime maintained once every two days, or daily in times of high temperatures- well watered) then harvested and soil samples taken. See section 3.6 for further details on the selection of lettuce.

Results

The timing of kelp application prior to planting was a significant effect on lettuce mass ($p < 0.05$) (Figure 27). Masses of lettuce for kelp applied at the sowing stage (t0) were approximately 3.5 times greater than for decomposed kelp (4 weeks decomposition). The overall trend observed was for a greater lettuce mass as kelp was added closer to the sowing date.

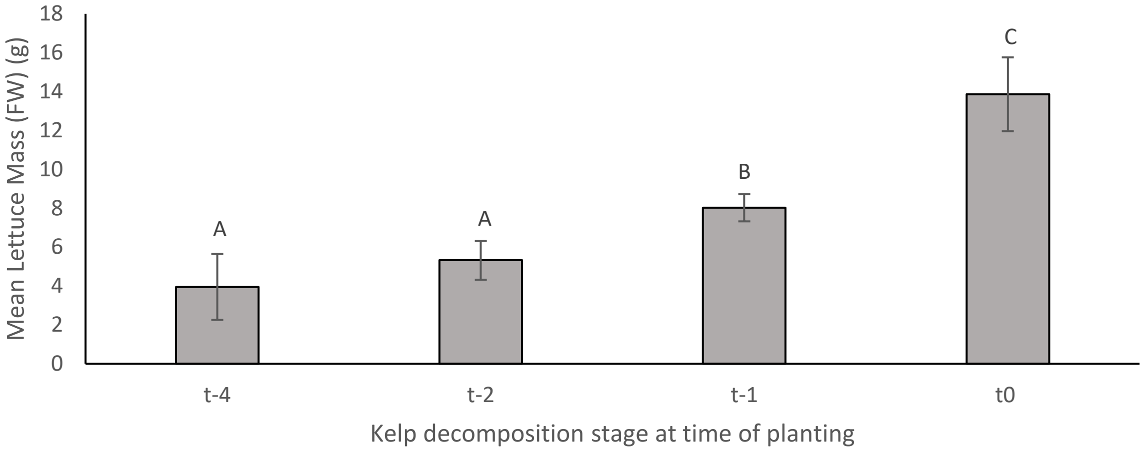


Figure 27 Effects of kelp fertiliser treatment (t0= fresh/ 0 weeks decomposed, t-1 = 1 week decomposed, t-2= 2 weeks decomposed, t-4= 4 weeks decomposed) on the mean mass of lettuce (Experiment 3.5) (Garden Experiment, Preston). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 20, 5 replicates, 4 treatments. Error bars represent standard deviation.

Discussion

The significant effect of timing kelp application on lettuce yield in this experiment, provides evidence for the potential benefits of using kelp-based fertilisers to support food production on marginal land. The results indicate that the timing of kelp application significantly influences lettuce productivity, with notable differences between treatments applied at different stages.

The increase in lettuce yield associated with kelp application at the sowing stage fresh kelp compared to the application of decomposed kelp (4 weeks), suggests that kelp additions closer to the planting date positively impacts crop yield. This finding aligns with the hypothesis that kelp, with its rich array of bioactive compounds and nutrients, can exert a more pronounced and immediate positive influence on plant growth and development when applied to the soil in closer in time to the germination and early growth stages of the crop.

The observed trend of increasing lettuce yield as the timing of kelp application approached the sowing date is consistent with previous studies exploring the effects of seaweed-based amendments on crop performance. The bioactive compounds present in kelp, such as cytokinins, auxins, and trace elements, are known to stimulate plant growth and enhance nutrient uptake. The more immediate availability of these beneficial compounds when kelp is applied closer to planting likely contributes to the observed positive correlation between kelp application timing and lettuce yield.

There is no current published research exploring how the timing of kelp application affects plant growth, however previous research presented in this chapter (Experiments 3.1. and 3.2) found that fresh kelp outperformed decomposed kelp and seaweed extracts. Taken together, these experiments emphasise the importance of considering the timing of application and pretreatment (length of time prior to application from collection) as a critical factor influencing its efficacy. While previous studies have demonstrated the overall positive impact of macroalgae on crop growth and yield (Cole et al., 2016, Knox et al., 2015, Possinger & Amador, 2015), this study for the first time contributes a valuable layer of information by highlighting that the temporal proximity of kelp application can significantly modulate its effects.

Furthermore, these findings demonstrate the importance of implementing kelp applications at the most effective timing, such as during sowing. Thus, potentially enhancing crop yields, however, further research is needed to explore the underlying mechanisms governing the observed temporal effects and to validate these findings across diverse environmental conditions and crop varieties.

The results of Experiment 3.5 highlight the importance of considering the timing of kelp application and its level of decomposition prior to planting in agricultural practices. The observed increase in lettuce yield with closer proximity of kelp application to the sowing date i.e., lettuce in a less decomposed state aligns with the current understanding of the beneficial effects of kelp-derived bioactive compounds on plant growth. These findings contribute to the ongoing efforts to refine agricultural practices and enhance crop productivity through the strategic use of seaweed-based amendments.

3.8 Discussion-Changes in Soil Properties

Fertiliser treatment significantly affected crop yields. Applications of fresh kelp as a fertiliser in traditional Lazybed systems resulted in increased yields in potato crops. The results revealed that when fresh kelp was added to cropping systems during the planting phase, potato production was stimulated, unlike applications of dung, decomposed kelp, mixed kelp+dung, commercially available bagged manure, and commercially available liquid fertiliser containing seaweed extract. The effect of fertiliser type on potato yields could be explained by the individual properties of the fertilisers and direct effects on plant growth, or through inducing changes to soil properties. In the fresh kelp systems, fertilisers resulted in changes to the following soils properties, nitrate, pH, C:N, soil moisture and soil carbon. However, some fertilisers resulted in changes in soil properties similar to those observed in the fresh kelp systems but did not result in increased crop yields. This suggests that the effect of the fresh kelp fertiliser on crop yields could be attributed to an alternate property, one which is not traditionally, accounted for in traditional measurements of soil fertility. Other researchers have found both positive and negative effects of seaweed amendment on soil quality (Possinger & Amador, 2016). Despite the negative effects of increased soil electrical conductivity and reduced N mineralisation rates observed under seaweed applications, crop yields increased (Possinger & Amador, 2016), supporting the findings presented in this chapter that the main effect of seaweed application is not due to indirect effects on soil quality, but potentially the presence of plant hormones in the seaweed amendment. Existing literature has demonstrated that the presence of plant hormones and specific growth regulators in fertilisers can stimulate plant growth (Ghaderiardakani et al., 2019; Zaman et al., 2015). Plant hormones such as gibberellins, auxins, cytokinins, abscisic acid, ethyleneglycine betaine and polyamines are all found in high concentrations in algal species. However, plant hormones rapidly degrade, through biological and physical processes, such as action by microbes and temperatures above 0^{o}C. Studies to assess growth hormones require tissues and substrates to be rapidly frozen in liquid nitrogen due to their volatility (Zaman et al., 2015). This finding is supported by other studies which have added seaweed extract in non-nutrient limited conditions and observed significantly greater yields when the extract is used, suggesting that the crop enhancing properties of marine fertilisers are not attributed to nutrient levels (González et al., 2013). Other researchers have looked at differences between composted marine algae and extracts (Michalak et al., 2017). Cress grown with seaweed extract had higher levels of macro-nutrients (N, P, K) compared to cress fertilised with marine algae-derived compost. This enhanced productivity in seaweed-fertilised crops may be attributed to changes in soil microbial populations. Commercial seaweed extract has been shown to increase soil microbial community diversity (Renaut et al., 2019), leading to improved soil function. The increased diversity results in the secretion of a broader range of extracellular enzymes, making a wider array of substrates available for plant uptake. Specifically, seaweed fertilisers boost the activity of key enzymes such as protease, polyphenol oxidase, and urease. Protease breaks down organic N-containing proteins into amino acids, directly accessible to plants (Werdin-Pfisterer et al., 2009), while urease plays a crucial role in urea mineralisation (Cordero et al., 2019). Phenol oxidase breaks down soil phenols, preventing their accumulation and ensuring the proper functioning of other soil enzymes, thereby promoting efficient soil nutrient cycling (Sinsabaugh, 2010). First, the direct impact of plant growth hormones present in the kelp fertilisers plays a role in these changes. These hormones likely interact with the plant physiology, promoting growth and development. Second, an indirect effect is associated with the alterations induced in the microbial community by the introduction of kelp fertilisers. These microbial changes, in turn, contribute positively to plant growth, possibly through enhanced nutrient availability or other symbiotic interactions.

It is likely that both the presence of plant growth hormones and the priming effect on the soil microbial community are mechanisms contributing to the observed increases in plant growth. However, to gain a comprehensive understanding necessitates a closer examination of the specific effects size attributed to each of these factors. Further research is crucial to precisely quantify and differentiate the direct influence of plant growth hormones and the indirect impact on the microbial community, elucidating the extent to which each mechanism contributes to the overall enhancement in plant productivity.

The effectiveness of fresh kelp to increase crop yields more than composted kelp and traditional manure and dung-based fertilisers, is reflected in the results from Experiments 3.1, 3.2 and 3.5. Despite, the relatively short decomposition periods examined in the timing of kelp additions (Experiment 3.5), clearly demonstrated the drop off in yields as time between fresh kelp additions and planting increased and could be due to the rapid degradation of plant growth hormones in the environment, however this was not measured.

Only extracts are utilised in many applications of macroalgae. It is likely that during the extraction process many highly labile compounds are lost as shown by the effects of fresh kelp on yields in comparison to the commercially available liquid fertiliser containing seaweed extract and the decomposed kelp. Although the addition of kelp in Experiments 3 and 4 did not result in reduced crop yields, evidence suggests that excessive concentrations of fresh seaweed extract may decrease plant vigour due to increased salinity (Blunden et al., 1997). However, it is important to note that the experiments used a closed system with soil-free media. Differences in thresholds could be attributed to the active transport of Na+ to lower depths of the mesocosm soil during watering, potentially maintaining optimal growing conditions in the upper mesocosm where the seeds were planted.

3.9 Conclusion

The field growth trials with different organic fertiliser treatments, as well as the controlled environment glasshouse trials, consistently demonstrated that the utilisation of kelp as a fertiliser enhanced crop yield. Yields from fresh kelp-fertilised plots were markedly greater than traditionally applied fertilisers such as dung and manure, as demonstrated during two growing seasons at two locations. However, the theorised effects of fertilisers on crop growth through changes to traditional soil properties was found not to correlate to enhance crop productivity in potatoes. This is supported by the changes in pH and other soil characteristics that were linked to the application of kelp+dung in Experiment 3.1. Despite alterations in crucial soil properties known to impact plant growth being less pronounced than those observed in kelp+dung, yields in these treatments fell below those treatments where singular additions of kelp were used as a fertiliser.

Key findings of the experiments detailed in this chapter are:-

1. The type and form of kelp-based fertilisers significantly influenced their effectiveness. Fresh kelp outperformed other forms, and commercially available seaweed extract showed limited efficacy. (Experiment 3.2, Experiment 3.5)

2. Synergy with organic amendments: Combining kelp with organic amendments, such as dung/manure, demonstrated synergistic effects on soil properties. (Experiment 3.1)

3. Yield- fertiliser application rate dependent relationships: The experiments highlighted the importance of precision application, indicating application rate-dependent yield responses in various crops. (Experiment 3.3, Experiment 3.4)

The conclusions drawn from this chapter's research should be assessed in light of the limitations inherent in the chosen methodology. A major limitation of the experiments undertaken in this chapter is the range of crops trialled. Ideally, it would have been better if the potatoes had been used across the five experiments but due to space limitations in the laboratory setting (necessitated due to travel restrictions imposed during covid) and time limitations (potatoes require a significantly longer growing period prior to harvesting than lettuce, and the spring barely experiment had to be ceased early due to the onset of the Covid-19 pandemic). If potatoes had been used across the four experiments this would have allowed for direct comparisons to be made.

In summary, the findings collectively underscore the complexity of the interactions between kelp-based fertilisers, crops, and soil properties. The studies emphasise the need for careful consideration of factors such as application rate, form, and timing for optimising the positive impacts of kelp-based fertilisers on crop production and soil health.

There are still uncertainties regarding the long-term impacts of adding kelp to soils and how these effects compare with conventional soil amendments i.e., dung/manure/inorganic fertilisers, especially considering the effect of salinity on yields. Additionally, there is a need to further investigate the mechanisms driving the differences in plant growth observed between the addition of fresh kelp and decomposed kelp, and whether specific rapidly degrading compounds in fresh kelp are responsible for driving these differences.

4 Effects of Reduced Watering on Crop Growth Modified by Kelp and Manure Additions

4.1 Introduction

The threat of drought is increasing as climate change progresses and lower yields caused by drought further complicate a stressed food production system. Bringing back areas of marginal land into food production, such as Lazybeds in Northwestern Europe, could play a role in future sustainable agricultural systems (Chapters 1 and 2). However, it is essential that these recultivated areas are resistant to current and predicted climatic stressors such as drought. Since the agricultural and industrial revolutions, land use change and the burning of fossil fuels, has caused greenhouse gases (GHGs) which trap infra-red radiation in the form of heat, to accumulate in the atmosphere. This heat is then circulated in the atmosphere and has caused the Earth's atmosphere to warm by 1.1 ^{o}C since 1880 (IPCC, 2023). This increase in global temperature threatens ecosystem functioning and service provision (Montoya & Raffaelli, 2010; Mooney et al., 2009; Shaw et al., 2011). More energy in the atmosphere, is disrupting weather patterns making drought and flooding events more likely (Greg, 2009; Konisky et al., 2016). These changes in temperature and moisture levels, are affecting carbon cycling on a global scale, leading to positive feedbacks (Cox et al., 2000). However, there are significant knowledge gaps with regards to the effects of reduced water availability on primary production. Consequently, urgency is required to create agricultural systems which are sustainable and resilient to the pressures of climate change.

Climate change may result in changes in the geographical range of many crops, with previously unsuitable areas now suitable for crop production (i.e., marginal land becomes less marginal) and vice versa (Olesen et al., 2011). By designing cropping systems which are more resilient to drought, yields can be retained for longer without the need to move the location of the food production system, giving a greater time to adapt the farming and food infrastructure at a global scale (Altieri et al., 2015).

Relatively little is known of the effect of kelp-based fertilisers on crop resistance to reduced watering. Phytohormones in extracts from the seaweed *A. nodosum* are known to support reduced watering tolerance in various crops, such as soybeans (Shukla et al., 2018). To mitigate the impact of reduced watering on plant growth and functioning, the plants biological, physical and chemical response to stress must be understood. Current understanding indicates that altering root and leaf structure and stomatal response offer the greatest potential to develop resistance to reduced watering stress in crops (Iqubal, 2022).

Land use strategies are known to affect the drought resistance of a variety of crops. A comparative study between effects of reduced watering on intensively managed wheat cropping systems in comparison to grassland systems, found that fungi were more resistant to reduced watering than bacteria (Birkhofer et al., 2021). Thus, in soils with fungal-dominated microbial communities, soil supported functions such as plant productivity are also more resistant to reduced watering(Birkhofer et al., 2021). One of the main factors in determining whether a soils microbial community is dominated by fungi or bacteria is the availability of nitrate (Homyak et al., 2017).

Plant health relies on water, serving a vital role in both photosynthesis and providing structural support. Insufficient watering conditions can significantly diminish plant productivity, leading to decreased crop yields. Inadequate soil moisture hampers water absorption by roots and stomatal conductance. Consequently, during periods of reduced watering stress, plants allocate more energy to root growth, impeding above-ground development. The decrease in stomatal conductance not only impacts CO2 uptake but also diminishes photosynthetic capacity. Furthermore, diminished water availability negatively influences plant defence mechanisms, rendering plants more susceptible to pests and diseases (Elad & Pertot, 2014).

Organic fertilisers are known to enhance crop resistance to reduced watering in both C3 (barley) and C4 (millet) photosynthetic pathway crops, particularly under warmed conditions (Januškaitienė et al., 2021). In comparison to inorganic fertilisers, organic fertilisers mitigate the reduction in photosynthetic rate and increased enzymatic antioxidant production in barley by 44% under warmed reduced watering conditions. Studies indicate that reduced watering negatively affects micro- and macronutrient content, as well as growth and physiological traits of crops. However, the application of organic fertilisers has been shown to alleviate these impacts, highlighting their potential in enhancing crop resilience to reduced watering stress (Geremew et al., 2021; Januškaitienė et al., 2021). Relatively little is known of the effect of kelp-based fertilisers on crop resistance to reduced watering. Furthermore, additions of kelp as a fertiliser not only add macro and micro nutrients but also other compounds such as phytohormones, alginate and organic matter (Haslam & Hopkins, 1996).

Alginate is a hydrophilic compound and is found in the cell walls of brown algae such as Laminaria digitata. In cell walls alginate functions to form a viscous gel, when bound with water. Alginate can be commercially extracted from algae and incorporated into the growing media to improve water management, by increasing the water holding capacity of the growing media e.g., soil. In horticultural systems the use of alginate-based hydrogels, has been found to result in an 80% increase in fresh weight of the plants grown in substrate supplemented with 5% hydrogels compared to control substrate after 7 days under reduced watering conditions (Tomadoni et al., 2020). It is likely that as fresh kelp decomposes alginate particles are released into the soil, enhancing water holding capacity. By increasing the amount of water originally held within the soil structure this infers more resistance to periods with no watering providing additional benefits for crop growth.

It is therefore essential to develop farming methods which are resilient to reduced watering and healthy, well-functioning soils are the foundation of this. As widely demonstrated, adding organic fertilisers can underpin soil-water functions, increasing water retention and in turn moisture content (Geremew et al., 2021; Hijbeek et al., 2016), however, the use of algae as a fertiliser potentially provides greater benefits due to the alginate and phytohormone content along with organic matter and macro and micronutrients.

The series of experiments presented in this chapter aim to increase our understanding of how the type of fertiliser used can affected the resistance of crop growth to drought conditions. This chapter employed a range of glasshouse and laboratory experiments to try to further disentangle the effects and interactions of fertilisers and drought on plant growth in a controlled environment. Specifically, this chapter seeks to make initial assessments of how spring barley grows in reduced watering regime conditions and whether the use of kelp as a fertiliser affects the growth response to said reduced watering regime conditions. To further support this, a follow up experiment was conducted to test whether the response of kelp fertilised crop (namely lettuce) under reduced watering regime conditions differs from crops which have been fertilised with manure. There are no historic records of lettuce being cultivated in Lazybeds; however, communities are actively encouraged to engage in lettuce cultivation as part of sustainability initiatives (Sustainable Uist, 2012). In addition, lettuce was chosen due to its rapid growth thereby shortening the experiment. Initial plans only intended for one reduced watering regime experiment to be presented in this chapter, however, due to the onset of the COVID-19 pandemic, Experiment 4.1 had to be halted early. Experiment 4.2 was therefore designed to expand on the early findings from Experiment 4.1, with manure also used as a comparative amendment. Both experiments had the broad aim to assess whether adding kelp fertiliser could modify the impact of reduced watering on crop production. Specific objectives were to:

i. Record changes of soil properties with addition of kelp fertilisers in well-watered and reduced-watered regimes.
ii. Measure crop growth with addition of kelp fertilisers in well-watered and reduced-watered regimes.
iii. Compare soil properties and crop growth in kelp-fertilised (unconventionally used organic fertiliser) treatments with manure (conventionally used organic fertiliser) and control (no fertiliser) treatments.

A range of hypotheses were tested in this chapter and are set out below by experiment:

Experiment 4.1.

Kelp fertiliser amendments alter the resistance of crop growth to a reduced watering regime.

Experiment 4.2

Kelp and manure fertiliser amendments alter the resistance of crop growth to reduced watering.

4.2 Methods

Two experiments are detailed in this chapter. Experiment 4.1. conducted in 2020, and Experiment 4.2. conducted in 2022.

Experiment 4.1. The response of Spring Barley to reduced watering modified by kelp additions. Materials and Methods

Large clods (approximately 20 x 20 x 20 cm) of intact soil were removed from close to the Harris, Isle of Rum, UK, experimental field site in July 2019 (Section 2.2) and then transported to Preston, Lancashire, UK. These clods were stored outside in containers, in a shaded area exposed to the rain for 6 months. This was to try to mimic field conditions as it was not possible to commence the experiment immediately, so that the soils retained as much as their field properties as possible, however, it is acknowledged that certain properties may have been altered during this storage phase. In the 4 weeks prior to the start of the experiment, the average temperature in Preston was 5 ^{o}C and there was 168 mm of rainfall. The soil was saturated; however, drainage had ceased. Plastic piping (PVCu) (11.5 cm diameter, B&Q) was cut to 15 cm lengths. Plastic mesh, (2 mm aperture) was cut into squares and sealed to the pipe at the base using high strength duct tape.

Spring barley (*Hordeum vulgare*, variety Irina, Cotswold Seeds Ltd.) was procured in November 2019. Preliminary testing was conducted to assess the viability of the seed for use in this experiment. These tests revealed a high germination rate, and that direct planting was the best method as transplanted germinated seeds had suppressed growth and survival rates in comparison to the directly planted seeds. Kelp was processed as described in section 3.5. The amount of kelp used in each sample added to the pots was calculated based on an optimum planting application rate of 90 kg N ha^{-1} (Teagasc, 2018). Based on the surface area of the mesocosm (104 cm^2), this equated to 10 g of fresh kelp (~60% moisture content) added to each mesocosm. On the 21/01/20 the soil collected at Harris, Rum, was passed through a 10 mm sieve to homogenise and remove any stones and pieces of vegetation.

The mesocosms were prepared and planted up on the 21/01/20. A base layer of gravel (300 g, gave approximately a 1 cm layer) was used to allow for good drainage of the cores. On top of the gravel, the main layer of soil was added (850 g), where the treatment was specified, the top 5 cm of the mesocosms had the cut kelp thoroughly mixed by hand into the profile and 3 barley seeds planted per pot to 3 cm depth, evenly spaced in a triangular formation. These are referred to hereafter as the *establishment mesocosms*. The intended watering regime for the establishment mesocosms was 100 ml and 50 ml twice per week for the control and reduced watering treatments respectively. The mesocosms were placed in designated control and reduced watering trays to prevent excess water being up taken by the reduced treatment mesocosms. Half the pots had a reduced watering treatment applied (fully factorial design with the kelp treatments), giving four distinct treatments, kelp-reduced watering, kelp-control, no additions-reduced watering, no additions-control. With five replicates per treatment, this gave a total of 20 establishment mesocosms.

This same design was repeated for a set of smaller mesocosms, however this time the amount of soil used in the relevant treatments pots was changed to 550 g. These secondary smaller mesocosms allowed for an assessment of both above ground and below ground growth during the first 4 weeks of the experiment, hereafter these mesocosms are referred to as the *initial mesocosms*. Although the pots used in the initial mesocosms were shallower than the establishment mesocosms, the amount of kelp added was the same as the surface area was the same. Watering regimes for these mesocosms was calculated relative to the size of the pot compared to the establishment mesocosm so in theory gave the same level of moisture availability in the soil. The ideal moisture content for reduced watering mesocosms was 30%, and 60% for control mesocosms. Initial soil moisture content was 60%. These values were used to calculate ideal mesocosm masses for the establishment and initial mesocosms. However, it is acknowledged that moisture content was not continuously controlled during this experiment and that in between watering soil moisture content fell below the desired water levels. However, it is unlikely that the control mesocosms would have experienced prolonged water restricted conditions, due to the high watering frequency. Twice weekly weighing was used to indicate the level of moisture in the mesocosms, with watering regimes adjusted accordingly. The mesocosms were arranged in a rectangular formation (3 x 7) with a blank plot inserted to make the layout uniform. The mesocosms were shifted over one space every two weeks to remove edge effects. Four germination trays with the treatments were also set up (Experiment 4.1.1), to compliment experiment 4.1. Here the spring barley seeds were planted on trays filled with John Innes seed starter, either with or without additions of kelp. John Innes composts are extensively used in research, with the seed starter standard used in this experiment, as this compost has the lowest nitrogen, phosphorus and potassium contents of the available composts, and has a finer structure more suitable for the promotion of germination (Bunt, 1963). Macronutrient contents for John Innes seed starter are N 5.1%, P 3.2% and K 8.1%) (Bunt, 1963). The amount of kelp added to the tray was calculated based on the pot surface area. Again, the same reduced watering and kelp treatments were applied to these trays (Figure 28). One hundred seeds were planted on each tray, giving 400 in total. The climatic conditions in the glasshouse were set to 21 °C and 41% relative humidity, with 13 hours light, which was responsive to external light conditions, to maintain a constant lux. At the end of this experiment, it was not possible to conduct the planned assessments of soil moisture, LOI, pH and macro and micro nutrients due to the onset of the COVID-19 pandemic.

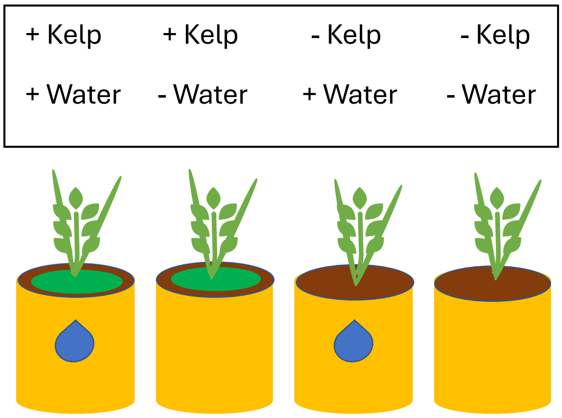


Figure 28 An illustration of the treatment combinations used in Experiment 4.1. Is the response of Spring Barley to reduced watering modified by kelp additions?

Experiment 4.2. Is the response of lettuce growth to reduced watering modified by additions of organic fertilisers? Materials and Methods

A fully factorial experimental design was used to assess how additions of kelp and manure can mediate the response of crop growth in reduced watering and ambient watering environmental conditions. Each of the 6 experimental treatments (fertiliser treatment (control/kelp/manure) X moisture stress (with/without)) was replicated 5 times, giving 30 treatment mesocosms. The 0.5 L pots (B&Q) were lined with a mesh and a 1 cm base layer of gravel. Each mesocosm was filled with John Innes no. 2 compost, and left to soak in water for 24 hours, after this time the pots were removed from the water and left to drain off excess for a further 48 hours. The pots were then reweighed, and an additional pot placed in the oven at 105 ^{o}C until a constant mass was reached to determine moisture content (field capacity). Kelp was incorporated by hand into the top 5 cm of soil in 10 of the mesocosms: this was fresh, recently collected from the Anglesey shoreline, washed and cut into 2 cm^2 pieces and homogenised. The kelp was then assessed for N content and was added to the pots at a rate of 65 kg N ha^{-1}, in line with N requirements for lettuce crops (ADAS, 2024). Commercially available cattle manure (B&Q) was added to 10 of the pots, at a rate of 65 kg N ha^{-1} (5 g). The N content of both the manure and kelp was determined, as in Chapter 3, through C:N analysis and the mean moisture content of the materials. For the control treatment, 10 mesocosms received no soil amendments. The mesocosms were then placed in a sterilised growth chamber. The growth chamber was fitted with lights (Mars Hydro TS600 100 W full spectrum LED) and a fan, which were both powered for 14 hours per day, with the latter to keep the chamber at ambient temperature conditions. Humidity was not controlled or monitored but should have been constant for each of the mesocosms in the growth chamber. Lettuce was chosen as the experimental crop, due to its rapid growth and high nutrient requirements. Three lettuce seeds were initially added to each pot and after 10 days the pots were thinned, leaving only the strongest lettuce seedling. Throughout the duration of the experiment, the moisture was monitored every two or three days, with amount of water added determined by the mass of the mesocosm (Earl, 2003): 30% moisture content for reduced watering, 60% moisture content for ambient watering (Figure 29). At the end of the experiment, the lettuce was carefully removed from the pots and separated into above and below ground biomass. Fresh mass for the above and below ground was determined, prior to oven drying at 60°C. The soil from the pots was passed through 2 mm sieves to homogenise prior to subsampling for analyses. Fresh soil subsamples were taken for moisture and LOI, nitrate content and pH. These soil samples were first passed through a 2 mm sieve, oven-dried at 105 °C until a constant mass was reached, then placed in a furnace at 535 °C for 4 hours to determine moisture content and loss on ignition ((LOI) to give an indication of organic carbon content), respectively (Rowell, 2014). The pH was determined by adding 5 g +/- 0.1 g of substrate to a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific), plus 25 ml of deionised (DI) water, inverted at 5-minute intervals for 30 minutes, then the liquid phase filtered through Whatman no. 1 and measured using a Hanna Edge probe (Rowell, 2014). To assess nitrate, 5 g +/- 0.1 g of substrate was put into a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)) and shaken and inverted by hand for 1 minute at 10-minute intervals for 2 hours and filtered through Whatman no. 1 and analysed on a Nitrachek 404 Meter + Test strips Kit (KPG Products Ltd) (Kang et al., 2005).

Further, the kelp and manure fertilisers were tested for micro- and macronutrient content and moisture content. For this, 10 x 10 g sub samples were taken of the kelp and manure and composited. The kelp and manure composite samples underwent air drying until a stable weight was achieved, and these weights were employed to determine the moisture content. Subsequently, the dried fertiliser sample was utilised to evaluate both macro and micro nutrient levels (see section 3.2.2 for detailed methods).

Results were statistically analysed using SPSS (two-way ANOVA, with Tukey's post hoc analysis) to determine whether there was an interaction between organic (kelp or manure) additions and reduced watering on lettuce growth.

Figure 29 Experiment 4.2 prior to harvest with experimental treatments arranged in rows.

4.3 Results

Experiment 4.1. Is the response of Spring Barley to reduced watering modified by kelp additions?

Germination rates (Experiment 4.1.1) for all four treatments were > 85%, with slightly lower germination rates recorded in the reduced watering regime treatments. An analysis of the effects of kelp additions found five-fold increases in spring barley above ground biomass in ambient moisture mesocosms, above the no additions control mesocosm (Figure 30). By contrast, in the reduced watering treatments, kelp additions resulted in 1.5 times increase above the no additions reduced watering regime treatments. There was no significant treatment difference between no additions control and reduced watering. When kelp was used as a fertiliser, reduced watering decreased above ground biomass by 57%. ANOVA revealed that the addition of kelp and an induced reduced watering regime significantly affected above and below ground biomass ($p < 0.01$ and $p < 0.01$) respectively (Figure 31). The interaction between kelp additions and reduced watering was not significant at $p < 0.05$ but was significant at $p < 0.1$.

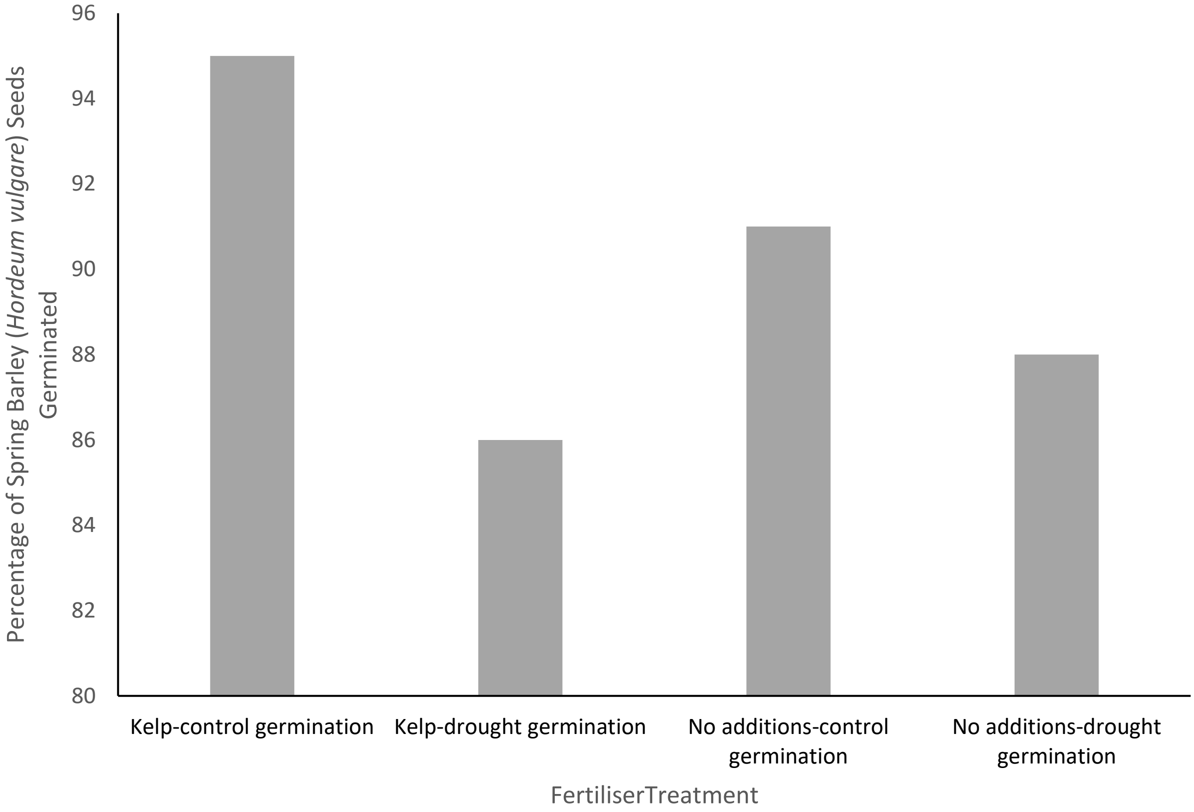
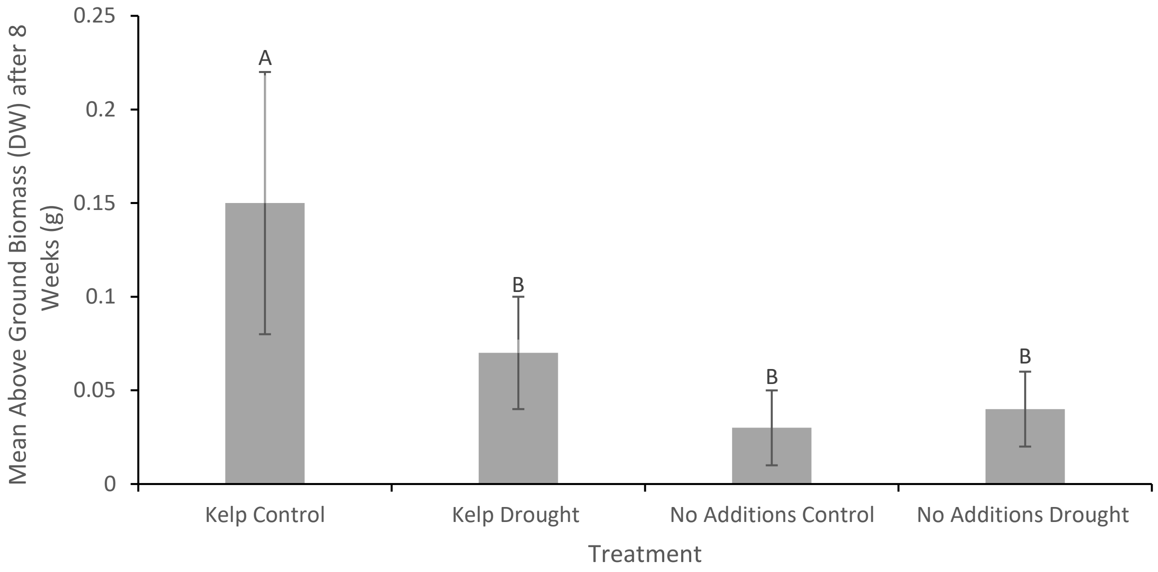


Figure 30 Effects of kelp fertilisers and a reduced watering regime on the percentage of Spring Barley seeds to successfully germinate (Experiment 4.1) (Myerscough Glasshouse). n= 100 seeds, 4 treatments.

A



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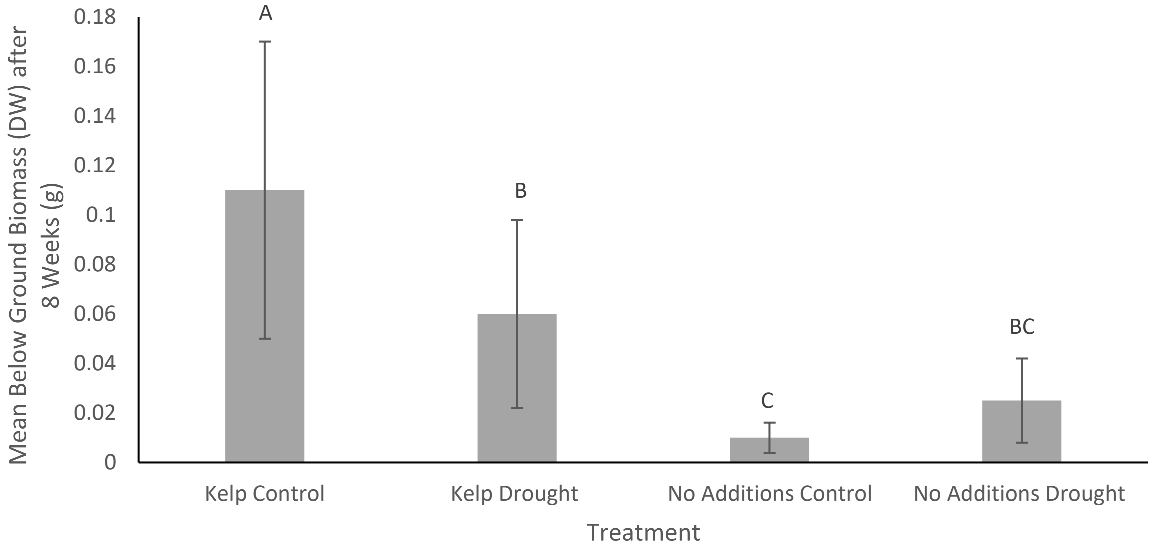


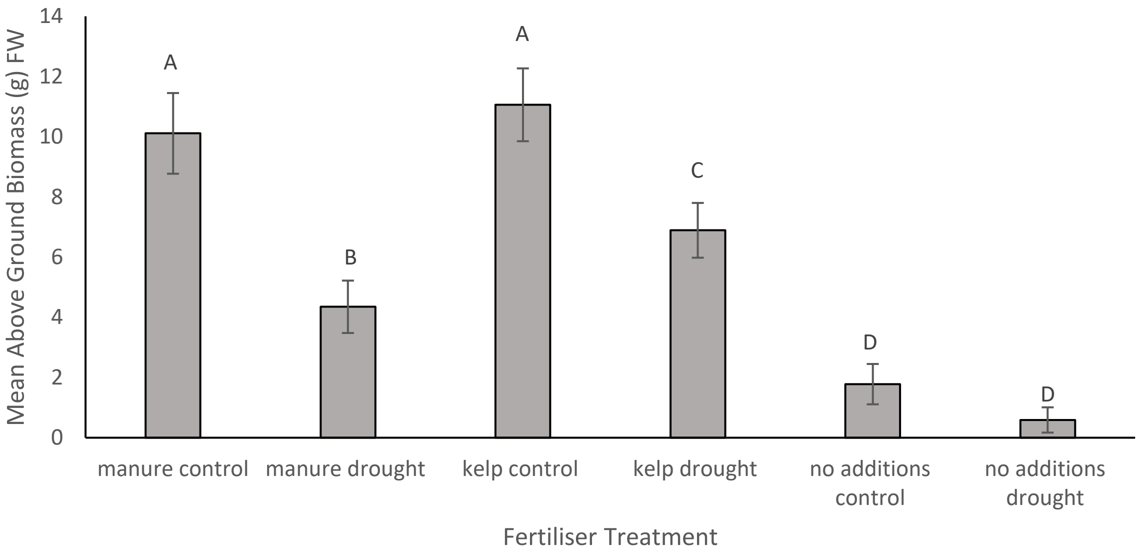
Figure 31 Effects of kelp fertilisers and a reduced watering regime on the mean (A) above ground and (B) below ground biomass of Spring Barley produced after 8 weeks of growth (Experiment 4.2) (Growth Chamber). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 20 mesocosms, 5 replicates, 4 treatments. Error bars represent standard deviation.

Experiment 4. 2. Is the response of lettuce growth to reduced watering modified by additions of organic fertilisers?

Lettuce growth was affected by fertiliser ($p < 0.001$) and reduced watering ($p < 0.001$) treatments for both the above and below ground biomass. Kelp-fertilised mesocosms under controlled water conditions (well-watered) had 10% greater growth than the manure control mesocosms, and 612% greater growth than the unfertilised control mesocosms (Figure 32).

The difference in above to below ground biomass ratio for the control and reduced watering treatments is indicative of changes in resource allocation (Figure 33). In the manure-fertilised and the no additions mesocosms, reduced watering conditions resulted in a greater root mass production. No change in resource allocation was observed for the kelp-fertilised mesocosms.

A.



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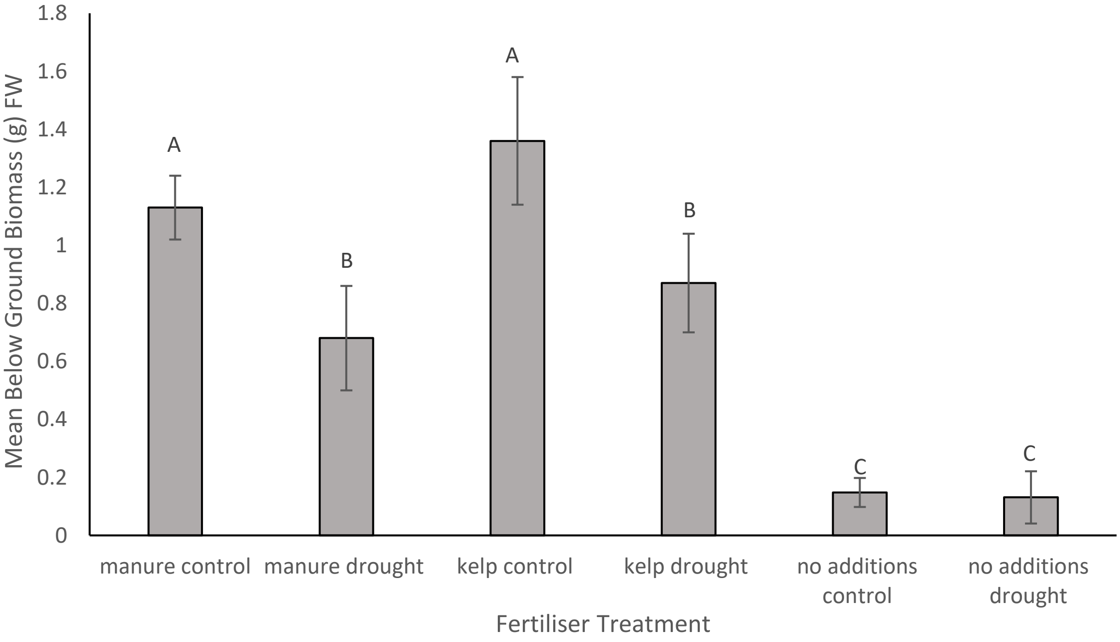


Figure 32 Effects of kelp and dung fertilisers and a reduced watering regime on the mean (A) above ground and (B) below ground biomass of Lettuce produced (Experiment 4.2) (Growth Chamber). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 30 mesocosms, 5 replicates, 6 treatments. Error bars represent standard deviation.

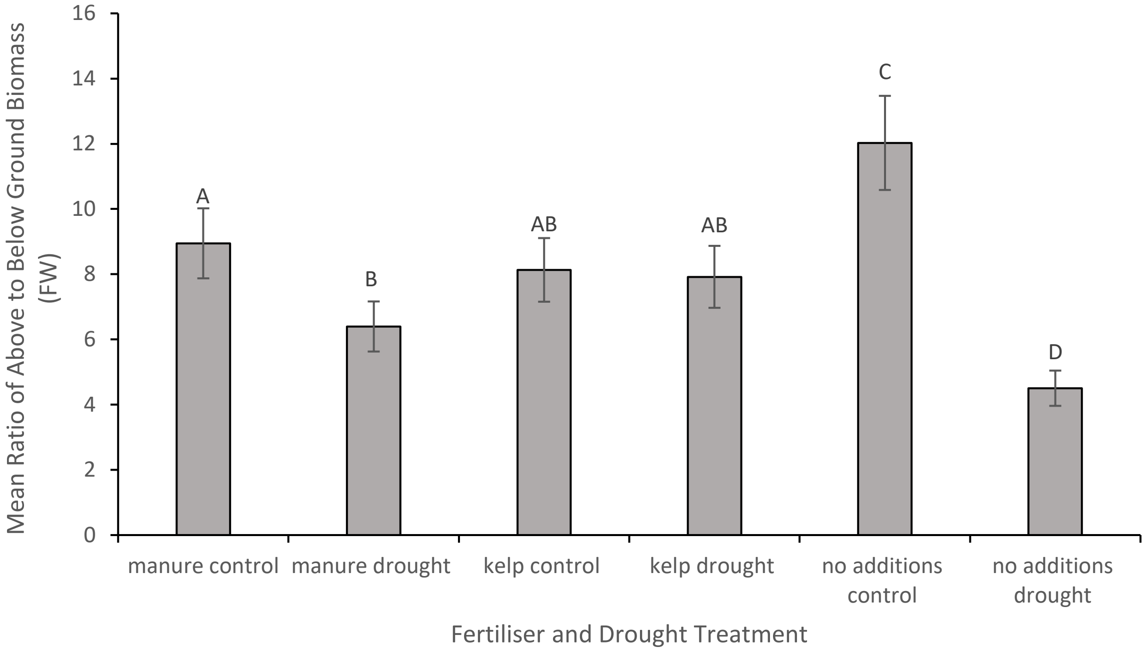


Figure 33 Effects of kelp and dung fertilisers and a reduced watering regime on the mean ratio of above ground to below ground biomass of lettuce produced (Experiment 4.2) (Growth Chamber). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 30 mesocosms, 5 replicates, 6 treatments. Error bars represent standard deviation.

Soil nitrate values were affected by fertiliser treatment ($p < 0.01$). Kelp and manure had similar levels of nitrate availability in the soils at harvest, with soil nitrate values in the no additions control 67% lower (Table 4). Reduced watering was also found to be a factor controlling soil nitrate concentrations, with reduced watering decreasing soil nitrate levels. The effect of reduced watering on soil nitrate was similar for both the manure and kelp fertiliser treatments. Soil pH was significantly affected by fertiliser treatment ($p < 0.01$), however reduced watering did not affect soil pH ($p > 0.05$) (Table 4).

Table 4 Soil data for Experiment 4.2.

Treatment	Mean LOI % (SD)	Mean Soil Moisture % (SD)	Mean Nitrate mg/kg (SD)	Mean pH (SD)
Manure Control	13.28 (0.97)	31.87 (2.88)	63.96 (3.19)	6.75 (0.67)
Manure Reduced Watering Regime	11.31 (1.57)	23.08 (2.64)	52.87 (5.11)	6.76 (0.82)
Kelp Control	10.91 (1.34)	27.18 (3.86)	68.09 (3.67)	6.91 (0.38)
Kelp Reduced Watering Regime	11.17 (1.80)	20.01 (2.51)	52.14 (2.68)	6.83 (0.22)
No Additions Control	9.23 (0.93)	20.74 (1.35)	20.02 (2.55)	6.53 (0.45)
No Additions Reduced Watering Regime	9.11 (0.82)	13.55 (2.13)	16.13 (2.94)	6.49 (0.24)

Soil moisture data provided further supporting evidence (in addition to the gravimetric watering data) that the reduced watering treatments were successfully applied over the course of the experiment (Table 4). No additions reduced watering had the lowest soil moisture content followed by the no additions control. The manure fertiliser treated mesocosm had greater soil moisture values than both the kelp control and the kelp reduced watering mesocosms. Soil moisture was significantly affected by fertiliser ($p < 0.001$) and reduced watering treatments ($p < 0.001$). The interaction between fertiliser and reduced watering treatments was not significant, however, this is by experimental design with moisture controlled throughout the growth phase.

LOI was significantly affected by fertiliser treatment ($p < 0.05$), however the effect of moisture regime and the interaction between the moisture regimes and fertiliser treatment was not significant (Table 4). Additions of manure and kelp increased LOI levels above that of the baseline substrate with no additions. LOI in the manure reduced watering mesocosms was lower than in the manure control mesocosm. However, in mesocosms fertilised with kelp, reduced watering did not result in a lower LOI value.

4.4 Discussion

The interpretation of results from Experiment 4.1, should be treated with caution due to the early cessation of the experiment, due to the onset of the COVID-19 pandemic. Thus, it is not possible to draw conclusions on how kelp may affect the resistance of crops to reduced watering, due to the limited growth of the unfertilised barley crop. Therefore, further research is needed in order to fully evaluate the hypothesis for Experiment 4.1- *Kelp fertiliser amendments alter the resistance of crop growth to a reduced watering regime*. It is likely that kelp could alter resistance to reduced watering due to the presence of alginates, which have hydrophilic properties, helping to bind water in the soil for longer periods mitigating the impact of reduced watering (Quastel & Webley, 1947).

Overall, germination rates across all treatments were within the expected range for spring barley (Teagasc, 2018), although there was a noticeable decrease in germination rates under a reduced watering regime. In the context of existing scientific literature, the observed germination rates align with previous studies on the impact of water availability on barley germination. Drought stress has been shown to negatively affect germination rates in various crops, including barley, as water scarcity imposes physiological constraints on seedling establishment (Fahad et al., 2017).

The increase in above-ground biomass in ambient moisture mesocosms with kelp additions suggests a positive influence of kelp on plant growth under optimal water conditions. However, it is likely that this observation in Experiment 4.1 could be due to the low nutrient content of the no additions pots (Rum soil which was used as a growing media in the mesocosms has a low nutrient (particularly N content) which is present in concentrations known not to be sufficient in supporting plant growth in Spring Barley (Teagasc, 2018). Experiment 4.1 did not seek to disentangle the mechanisms behind the growth responses to kelp and reduced watering, just to determine if in fact there was a difference. Whereas Experiment 4.2 addressed underlying mechanisms by controlling for N content, using manure as a comparative treatment. This finding aligns with existing literature, highlighting the potential benefits of seaweed extracts, such as kelp, as bio-stimulants for enhancing plant growth and development (Cole et al., 2016). The mechanisms underlying this growth promotion could include improved nutrient uptake, hormonal regulation, and stress tolerance conferred by the bioactive compounds present in seaweed extracts (Iqbal et al., 2022).

The increase in above-ground biomass observed in the reduced watering treatments with kelp additions indicates that the negative effects of water limitation on plant growth may be partially mitigated through use of kelp as a fertiliser. This is consistent with studies demonstrating the dependency of seaweed-based bio-stimulants on adequate water availability for optimal performance (Chen & Pang, 2023; Iqbal et al., 2022). Although the interactive effect of kelp additions and reduced watering was not statistically significant at the conventional $p < 0.05$ level but exhibited significance at the $p < 0.1$ level, indicating a potential trend that warrants further investigation.

The ANOVA results indicating significant effects of kelp additions and induced reduced watering on both above and below-ground biomass highlight the importance of considering multiple growth parameters in assessing the overall impact of experimental treatments. These findings contribute to our understanding of the complex interplay between kelp-based bio-stimulants, water availability, and plant growth, shedding light on potential challenges and opportunities for optimising their application in agriculture.

In conclusion, the results of Experiment 4.1 underscore the complex relationships between kelp additions, water availability, and the growth of spring barley. The findings align with existing literature on the individual impacts of drought stress and kelp bio-stimulants, while also indicating that there may be interactive effects that merit further investigation. This study contributes information to the ongoing efforts to enhance agricultural sustainability and productivity in the face of changing environmental conditions.

Experiment 4.2 found that adding fertiliser modified crop growth response to reduced watering, supporting the hypothesis that kelp and manure fertiliser amendments alter the resistance of crop growth to reduced watering. In the unfertilised controls, the reduction in crop growth due to decreased watering was more pronounced compared to kelp and manure-fertilised mesocosms. Further, resistance to reduced watering was greater in kelp-fertilised mesocosms, compared to manure-fertilised mesocosms. This means that kelp not only acts as a fertiliser but can potentially promote resistance to reduced watering. This is likely due to modifications in the soil matrix resulting in improved water retention or the presence of biostimulants, although these were not measured in the scope of this experiment. Studies have found that under reduced watering stress conditions, the stem water potential of crops fertilised with brown seaweed (*Ascophyllum nodosum)* was greater for crops receiving higher concentrations of seaweed extract (Ghaderiardakani et al., 2019; Rayorath et al., 2008).

A common response to reduced watering stress is a shift in resource allocation with plants increasing root growth. However, in the current experiment (4.2), kelp-fertilised crops did not exhibit changes in the ratio of above and below-ground biomass, despite observed reductions in overall growth, whereas crops fertilised with manure and the no-fertiliser control showed a shift in resource allocation towards increased root growth.

Biostimulants are found in brown seaweeds such as kelp, they include cytokinins, betaine, and phenolics and have the potential to modify the plant’s response to water stress. Cytokinins, betaine, and phenolics contribute to a plant's ability to cope with water stress by promoting growth, maintaining cell turgor, and protecting against oxidative damage (Wahab et al., 2022). Understanding the roles of these compounds can inform strategies for improving tolerance to a reduced watering regime in crops and other plants (Ahluwalia et al., 2021). Specifically, cytokinins promote cell division and elongation, helping the plant to maintain growth even under limited water availability (Farber et al., 2016). Cytokinins can also regulate stomatal opening and closure, which affects water loss through transpiration. By influencing stomatal functioning, cytokinins can help plants optimise water use efficiency (Costanza et al., 1998). Betaine can protect cellular structures and enzymes from damage caused by dehydration, contributing to the plant's ability to withstand water stress (Ashraf & Foolad, 2007). Phenolics are a diverse group of secondary metabolites in plants, including flavonoids and phenolic acids (Zhang et al., 2022). They have antioxidant properties and play a role in plant defence against various stresses, including water stress (Dehghanian et al., 2022). Specifically, phenolics can bind reactive oxygen species, which are produced by plants in stressed conditions and can result in cellular damage (Wahab et al., 2022). In this experiment under the watering regime, when water stress was partially alleviated, kelp-fertilised crops may have demonstrated a stronger recovery response to applied water compared to manure-fertilised crops.

Other studies have found that during the early post-reduced watering phase i.e., immediately after water additions, plants treated with seaweed extract had a significantly higher stomatal conductance (Shukla et al., 2018). This was due to the seaweed extract regulating the biosynthesis of abscisic acid, which regulates stomatal closure, and thus photosynthesis. The more rapid the reduced watering response through the production of abscisic acid, the lowered risk of damage to the plant through excess water loss. Further, the heightened response due to seaweed extract-induced biosynthesis also results in a faster opening of stomata once the water limitation stress has been reduced (Shukla et al., 2018).

Soil nitrate concentrations were affected by reduced watering in this experiment, but not fertiliser treatment (as applications of kelp and manure were standardised by N content this is not unexpected). This is because water availability is a major control on microbial activity, which is responsible for the decomposition of organic fertilisers mobilising nutrients like nitrogen. Dry conditions limit microbial activity, through changes in community structure and physiology, subsequently slowing the rate of N cycling and making less available to plants (Homyak et al., 2017). Furthermore, in times of reduced watering stress, when stomal conductance is lowered, the uptake of water, which contains water soluble nutrients such as nitrate is reduced, meaning that even when nitrate stocks in the soil remain unchanged the uptake pathway is disrupted, reducing plant nutrition affecting crop growth.

Experiment 4.2 demonstrates the interactions between organic fertilisers, specifically kelp and manure, and their combined influence on lettuce growth under reduced watering conditions. The observed increase in lettuce growth with kelp fertiliser aligns with existing literature on seaweed-based fertilisers, emphasising their positive effects on plant growth and yield. The findings underscore the importance of fertiliser choice and resource allocation strategies in enhancing crop resilience and productivity, particularly in water-limited conditions. These insights hold practical implications for optimising agricultural practices and addressing water resources challenges.

The research findings from this chapter need to be viewed in the context of the methodological limitations that were present. A major limitation of the experiments undertaken in this chapter was the use of John Innes composts as a growing media. If natural soils had been used this would give a better indication of how the system would respond to a reduced watering regime and fertiliser inputs. Soil texture and chemical status between John Innes compost and soils from areas which were historically cultivated will have highly contrasting physical and chemical properties; properties which are already well established to be major controls on crop growth. However, due to the remote locality of the field site and the permissions required to abstract soils en mass from the Isle of Rum, it was not possible to transport the required large volumes of natural soil from historically cultivated lazybeds back to the lab/glasshouse for use in experimental purposes.

5. Interactions between Earthworms and Kelp Soil Amendments

5.1 Introduction

The availability of macronutrients in soils is key to support crop productivity (Hijbeek et al., 2016). In natural terrestrial ecosystems, the input of nutrients in the soil originates from leaf litter and rhizodeposits (Hoffland et al., 2020). Rhizodeposits are defined as all material input into the soil from the plant root system, this includes sloughed off root cells and tissues, water soluble exudates and secretions of insoluble materials (Pausch & Kuzyakov, 2018). However, in many cropping systems, the removal of the food, fibre or fuel product creates a nutrient deficient system over time, resulting in the need to replace soil nutrients (Kopittke et al., 2019). Soil macronutrients have been supplemented for millennia using plant and animal derived manures, referred to hereon as organic manures. In the Lazybed system, kelp and animal manure were often added to the soil to enhance fertility on marginal land. However, this practice became largely extinct as a consequence of the Highland Clearances and as agricultural technologies progressed (Darling, 1945). In the 20th century, the advent of the Harber-Bosch Process led to the production and widespread use of inorganic NPK fertilisers, referred to from here as inorganic fertilisers.

Earthworms, along with other soil fauna and microbial populations, are central to the cycling of nutrients in a variety of ecosystems, which are essential for the promotion of plant growth (Edwards & Arancon, 2022; van Groenigen et al., 2014). Dead organic material, including that contained within animal excrement, containing nutrients that plants have taken up during life, is ingested by earthworms (Edwards & Arancon, 2022). Most of this dead organic material passes through the worm, with the worm assimilating a small proportion of the energy and nutrients contained in the decaying vegetation. The organic material mixed with ingested soil, is then expelled as casts into the soil system. Existing research suggests that the fragmented material in the casts has physicochemical and biological properties which enhance plant growth over material which has not been ingested by earthworms (Atiyeh et al., 2000). Further, the presence of earthworms is understood to affect microbial diversity and biomass in composting manures (Aira et al., 2002).

Earthworms are known to influence key soil properties in a number of ways which promote soil health and thus crop growth. Earthworms are considered ecosystem engineers - species which modify, maintain or create habitats (Lavelle, 1997).

The effects of earthworms on soil functions could be essential in meeting the challenges of sustainable intensification (van Groenigen et al., 2014), to enhance global food security for a growing population and reduce negative environmental impacts of agricultural systems. Positive effects of earthworms on plant growth are well documented (Scheu, 2003), however, understanding the mechanisms underpinning increases in productivity are currently incomplete. In utilising earthworms to maximise positive impacts on agricultural productivity, it is essential to explore how earthworms interact with abiotic and biotic factors that affect ecosystem functions (Spurgeon et al., 2013; van Groenigen et al., 2014).

Understanding is extremely limited regarding the effect of Lazybeds (an historic agroecosystem (Chapter 1 and Section 2.3)) and their management on earthworm populations, and the potential role that earthworms may play to further enhance yields in these systems when under cultivation (Butt et al., 2020; Butt & Nuutinen, 2021). However, literature exists which pertains to how earthworms interact with soil moisture (a property that is likely to be influenced by Lazybed management) (Wever et al., 2001). Specifically, soil moisture significantly influences the activity and distribution of earthworms; their presence in turn has profound effects on soil functions and crop yields (Torppa et al., 2024). In very high or very low soil moisture conditions, earthworm activity is limited, as adequate soil moisture is essential for earthworms to maintain their physiological functions, move through the soil, and carry out activities such as burrowing and feeding (Edwards & Arancon, 2022; Singh et al., 2019). Soil moisture also interacts with the presence of earthworms to augment microbial decomposition processes, with optimal soil moisture conditions facilitating the breakdown of organic matter and nutrients in earthworm castings, contributing to improved soil fertility (Ganault et al., 2024).

Plant productivity in temperate, waterlogged soils is generally nitrogen (N)-limited (LeBauer & Treseder, 2008). Many historic Lazybed systems are situated on soils characterised as peaty gleyed-podsols, which have formed due to low temperatures and high moisture content, limiting microbial activity, resulting in a deep organic layer which has a low nutrient content (James Hutton Institute, 2019). The structure of Lazybeds specifically works to reduce waterlogging in these systems, with soil moisture being drained away from the elevated ridges into the furrows. Within the deep organic soil layer many nutrients are immobilised, bound to organic matter. A recent study has found that plant-soil N cycling in arctic systems, is further limited by the absence of earthworms (Blume-Werry et al., 2020). Comparisons may be drawn between the effects of earthworms in arctic soils and marginal soils in the Hebrides where the Lazybed system was commonly practiced, as both are characterised by low nutrient contents and high organic matter, however, differences in soils functioning between these soils will exist meaning direct comparisons cannot be made. Many nutrients in the organic layer of the arctic soils became more bioavailable due to earthworm action following introduction. Specifically, it is the mineralisation of N in litter and humus, coupled with the translocation of nutrients in the soil profile to root zones. Plant N concentrations were increased and led to increased plant height, floral shoot numbers, vegetation greenness and fine root biomass in shrubs and grasses. Interestingly, Barthelemy et al., (2015) also found that earthworm effects on plant N and greening were greater than observed effects of nutrient additions from reindeer urine and dung additions.

Perturbations to soil nutrient cycling through fertiliser and soil amendments are known to significantly affect earthworm ecology, leading to changes in soil functioning and crop yields (van Groenigen et al., 2014). The impact of organic and inorganic fertilisers on earthworms can vary based on factors such as the type of fertiliser, its composition, application rates, and the specific conditions of the soil (Deru et al., 2023). Generally, earthworms have been shown to respond positively to the use of organic fertiliser additions such as compost, manures, and other natural materials which provide a balanced mix of nutrients and organic matter (Deru et al., 2023). Earthworms are generally positively influenced by organic matter, as it serves as an energy source (Edwards & Arancon, 2022). However, as the ratio of nutrients (particularly N) to organic matter, becomes lower, such as in animal slurries with high readily available nitrogen content, earthworms can be negatively affected by the production of ammonia in their breakdown (Murchie et al., 2015). These slurries also can result in changes to soil pH, with soils becoming more acidic, negatively affecting earthworm populations (Murchie et al., 2015). Negative effects of fertiliser use on earthworms are greatest when excess nutrients are added without a co-input of organic matter, such as in inorganic fertilisers. Inorganic fertilisers have direct toxic effects on earthworms (*Eisenia fetida, Dendrobaena octaedra, Allolobophora parva*) when ingested, which has been attributed to the presence of heavy metals (Alengebawy et al., 2021), while also resulting in the reorganisation of soil food webs and the accelerated loss of organic matter (Van Der Heijden et al., 2008). However, other studies have found that the use of inorganic fertilisers positively correlates to earthworm populations, with the populations bolstered by increased vegetation growth (Edwards & Lofty, 1982). These contrasting observed effects may be due to different application rates, soil types, agricultural systems and study lengths. There is scope to investigate how other fertiliser types which may have been historically utilised, i.e., macroalgae, affect earthworm populations.

Knowledge is limited with respect to the feeding behaviour, individual growth and reproduction in earthworm populations where marine macroalgae is present as a food source (as seen when kelp is added to Lazybed systems as a fertiliser) (Butt et al., 2020). However, existing research shows that a high density of earthworms can be responsible for the turnover of strandline detritus (containing algal material) (Coupland & McDonald, 2008). In contrast, the application of a commercially available calcified seaweed product showed no effect on earthworm populations compared to liming and no additions in improved grasslands (Blackshaw, 1989). Further, research found that the application of seaweed extract did not significantly affect earthworm populations, however, the concentration of seaweed extract was found to affect the production of AMF spores and increase yields (Kilowasid et al., 2022). Earthworms are selective feeders and the source of organic material they ingest depends upon the ecological grouping i.e., endogeic which feed on soil organic residues, epigeic and anecic which are surface litter feeders (Bouché, 1972), which may lead to uncertainty with regards to feeding relationships between earthworms and algal species. Food preferences have also been demonstrated in experiments assessing the palatability of a variety of food sources with different species of earthworms (Butt et al., 2020). The quality of the food resource is also important in determining the health of the earthworm community with higher nitrogen content foods being preferred (Curry, 1998). An experiment which assessed earthworm feeding behaviours on different types of organic materials found that kelp was consumed by some species of earthworms (Butt et al., 2020). In addition to the cycling of nutrients earthworms play a key role in the bioturbation of the soil, enhancing structure and physical properties (Edwards & Arancon, 2022).

As kelp decomposes, its chemical composition changes, likely making it more palatable to earthworms. Prior to decomposition kelp contains an array of complex organic compounds, including phenols, which are known to have inhibitory effects on the feeding behaviours and growth of earthworms (Liebeke et al., 2015). However, during the decomposition of organic materials, phenolic compounds breakdown (Freeman et al., 2001). Additionally, the process of decomposition results in the release of salts from the kelp tissue (Gondek et al., 2020). The likely reduction in salt (Na) content enhances the suitability of decomposed kelp as a food source for earthworms, as excessive salt deters herbivory. Furthermore, the C:N ratio of organic materials often increases during the decomposition process, with the carbon-to-nitrogen (C:N) ratio increasing through the release/metabolism of nitrogen compounds, whereas earthworms generally preferentially feed on materials with a lower C:N ratio (Butt, 2011). It should, however, be noted that fresh kelp already possesses a relatively high C:N ratio compared to more conventional earthworm food sources (Butt et al., 2020). However, collectively these changes in phenol content and salt concentration could contribute to the increased palatability of decomposed kelp to earthworms, making it a potentially more palatable food source for earthworms.

This chapter details two experiments, with two further experiments presented in the Appendices 9.3 and 9.4. The overarching aim of this chapter is to assess whether earthworms can utilise kelp as a food source when it is used as a fertiliser in agricultural systems and whether the presence of earthworms can enhance the effectiveness of the fertiliser treatment. To address this the following hypotheses are presented below by experiment.

Experiment 5.1

The stage of decomposition for kelp affects its palatability to earthworms as a food source.

Experiment 5.2

The presence of earthworms in kelp and manure fertilised systems affects crop yields.

5.2 Methods

A suite of experiments was conducted in the UCLan laboratories: - 5.1. Effects of decomposition stage of kelp on earthworm feeding preferences and soil properties and 5.2. An investigation into how the legacy effects of earthworm food source (kelp and manure) affects selected soil properties and plant growth, for which methods are detailed below. Plus, two preliminary experiments- 5.3. An investigation of the effects of earthworm population density and kelp application (with and without kelp) on selected soil properties (Appendix 3), 5.4. A comparison of earthworm species fitness when kelp is given as a food source (Appendix 4), which were used to guide the design of the two main experiments.

5.2.1 Kelp Preparation

For each of the experiments undertaken, the kelp was prepared as described in section 3. The holdfasts and stipes were removed, leaving the blades, which were washed by submerging in 5 L of tap water and further rinsing in tap water using a hosepipe (20 L over 2 minutes) (Figure 34). This process was repeated 4 times with fresh water and served to removed surface salt residues and particles of shell, sand and other detritus from the blades. After processing the kelp was the stored at -20 °C until needed, after which it was defrosted and cut into approximately 2 cm^2 pieces.

Figure 34 Kelp after being rinsed to remove surface salt residues and debris.

5.2.2 Earthworm Collection and Husbandry

Earthworms for Experiments 5.1, 5.3 and 5.4 were collected from a semi-improved grassland at Bottoms Farm, Preston, UK (53.707310, -2.6762238), during spring and autumn months when the ground conditions were at the appropriate moisture level and temperature to find earthworms in the upper soil profile. The collection method used is well established and allowed for the capture of a range of earthworm species (Fründ et al., 2010; Lowe & Butt, 2005). Specifically, a ~ 0.35 m x 0.35 m x 0.2 m clod of vegetation and soil was dug out of the grassland and immediately upturned on to a non-permeable sheet. By hand searching through the pit and extracted clods of soil, adult earthworms were collected and placed in containers of soil for transport back to the laboratory. For experiment 5.2. *Lumbricus terrestris* were procured from Wigglywigglers.co.uk. In the laboratory the earthworms were checked for overall health and individuals showing signs of disease/damage were removed. The earthworms were positively identified as belonging to the species *L. terrestris* (using live characteristics, with a few specimens placed in formaldehyde prior to identification through microscopy). Healthy, adult (life stage identified through the presences of a clitellum) earthworms were thoroughly washed in clean cold water and separated by species. Four individual earthworms were placed in 750 ml tubs (Lakeland Plastics) of 25% moistened pre sterilised loam (Sterilised Kettering Loam, Broughton Loam Ltd.) mixed with oven dried and rewetted horse manure. Sterilised Kettering Loam (Boughton Loam Ltd., Kettering, UK), referred from here on as Kettering Loam as the product name “Sterilised Kettering Loam” may result in confusion over the sterilisation status of the soil. Kettering Loam is widely used for experimental research purposes including earthworm research (Ashwood et al., 2017; Langdon et al., 2005; Lowe & Butt, 2005; Turner et al., 2021). However, it is understood that the heat treatment sterilisation process used in the production of Kettering Loam (Boughton Loam Ltd., Kettering UK) would be ineffective at producing a fully sterilised growing media, further the water used in the experiment was not sterilised. Other research which required microbially sterile soils has recognised this shortcoming and when using Kettering Loam has undertaken subsequent sterilisation steps (Merino-Martín et al., 2021).

Care was taken over the provenance of the horse manure to ensure that the horses that produced the manure had not been recently treated with a de-worming product (traces of deworming products may kill or have sublethal effects on earthworms that ingest the manure). The tubs were sealed with lids containing four small air holes created using a mounted needle and placed in an incubator at 15 °C in constant darkness for a minimum of 30 days prior to experimental use (Fründ et al., 2010). Earthworms were periodically checked for food and water requirements and every 8 weeks the substrate was removed and replaced with new Kettering Loam and horse manure, whilst checking earthworm condition and removing cocoons and hatchlings.

5.2.3 Laboratory Analysis of Soil Samples

Soil samples from each of the experiments (Experiment 5.1 and 5.2) were tested for moisture and carbon content, pH and nitrate (as in section 3.2.3). These sub-samples were first passed through a 2 mm sieve, oven-dried at 105 °C until a constant mass was reached to determine moisture content.

The dried soil was then ground using a pestle and mortar and passed through a 0.5 mm sieve for analysis. The dried, sieved soil was then weighed into crucibles and placed in a furnace at 535 ^{o}C for four hours to determine LOI. The pH was determined by adding 5 g +/- 0.1 g of substrate to a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), plus 25 ml of DI water, shaken by hand for 1 minute at 10-minute intervals for 30 minutes, then the liquid phase filtered through Whatman no. 1 and measured using a Hanna Edge probe. To assess nitrate, 5 g +/- 0.1 g of substrate was put into a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), and shaken and inverted by hand for 1 minute at 10-minute intervals for 2 hours (Barillot et al., 2013)d and filtered through Whatman no. 1 and analysed on a Nitrachek 404 Meter + Test strips Kit (KPG Products Ltd) (Kang et al., 2005).

5.2.4 Effects of the Stage of Decomposition of Kelp on Earthworm Feeding Preferences and Soil Properties (Experiment 5.1)

A fully factorial experiment was used to assess how earthworms feed on kelp of differing levels of decomposition and if this influences soil properties. Three different levels of kelp decomposition, fresh kelp, decomposed kelp (2 weeks), and decomposed kelp (4 weeks) were used. To create the treatments, a 10 L bucket of kelp, covered with a fine mesh were left outside out of direct sunlight. After 2 weeks the kelp was mixed by hand and a subsample taken, which was then frozen at -25^{o}C until the start of the experiment. This process was repeated again 2 weeks later, creating the decomposed kelp (4 weeks) treatment. Fresh kelp was frozen shortly after collection and processing as described in section 3.2. These kelp treatments were added to tubs of 25% moistened Kettering Loam (Boughton Loam Ltd, Kettering, UK) either containing no earthworms or two adult *Aporrectodea longa.* There were five replicates per treatment.

A. longa were collected from natural earthworm populations in grassland systems in Lancashire in November 2021 and acclimatised to laboratory conditions (section 5.2.2 for details), kept in 750 ml tubs (Lakeland Plastics) of Kettering Loam (Boughton Loam Ltd), rewetted and fed with dried “deworming treatment-free” horse manure, until January 2022. At that time, healthy adults were selected for use and weighed and positively identified as belonging to the species *A. longa* (using live characteristics, with a few specimens placed in formaldehyde prior to identification through microscopy). Earthworms were added to pots standardised by weight with the combined weight of the two earthworms equalling 10 g +/- 1 g. The earthworms were added to new pots (section 5.2.2) containing Kettering Loam (Boughton Ltd. Kettering, UK) which had been rewetted to 60% moisture content and had the kelp at different stages of decomposition added (Lowe & Butt, 2005).

5.2.5 An Investigation into how the Legacy Effects of Earthworm Food Source (Kelp and Manure) Affect Selected Soil Properties and Plant Growth (Experiment 5.2)

A fully factorial experimental design was used to assess how the feeding actions of earthworms on kelp can impact soil fertility and subsequent crop growth. This experiment built on previous experiments which successfully demonstrated how earthworms will feed on fresh kelp, and how kelp additions act to change soil properties and promote crop growth (section 5.2.1, 5.2.2, 5.2.5 for overarching methods) (see Experiment 5.1, and preliminary Experiment 5.3. and preliminary Experiment 5.4. for full experimental details). However, from the results it was unclear as to whether the action of earthworms could enhance the effect of kelp additions.

Adult *Lumbricus terrestris*, procured from wigglywigglers.co.uk, were acclimatised to laboratory conditions, kept in Kettering loam (Boughton Loam Ltd.), rewetted and fed with dried horse manure, until December 2021 (see 5.2.2 for details) (Lowe & Butt, 2005). At that time, healthy adults were selected and positively identified as belonging to the species *L. terrestris* (using live characteristics, with a few specimens placed in formaldehyde prior to identification through microscopy) for use in this experiment and weighed. The earthworms were added to new pots (see 5.2.2) containing John Innes no. 1 which has been rewetted to 60% moisture content and had the appropriate levels of kelp added (based on a N application rate of 60 kg N ha^{-1}). The kelp was fresh, collected from the Anglesey shoreline, washed and cut into 2 cm^{2} pieces to be homogenised (see. 5.2.1 for details). Lids had small airholes made using a mounted needle. Over a period of four weeks the pots were regularly checked with moisture adjustments made where necessary e.g., if the substrate appeared to be too dry the surface of the substrate was sprayed with water (Lowe & Butt, 2005).

After four weeks the earthworms were carefully removed, disturbing the substrate as little as possible. The worms were then weighed. Then three lettuce seedlings (Salad Bowl, Thompson and Morgan) were planted in the pots, (lids not replaced), and transferred to a growth chamber containing lights and a fan (running on a 14-hour daylight cycle, Mars hydro ts-600, Manomano.com, Icycool, 4 inch black USB fan, The Range). The pots were checked on a biweekly basis and watered as appropriate.

After 10 days, the weakest seedlings were removed, leaving the strongest lettuce seedling in each pot. The growth phase of the experiment lasted for 8 weeks; thereafter, the lettuces were carefully removed from the pots manually and separated into above- and below-ground biomass. Fresh mass for the above- and below-ground biomass was determined, prior to oven drying at 60 ^{o}C. After oven drying, the above- and below-ground biomass were reweighed. The soil from the pots was passed through a 2 mm sieve to homogenise prior to subsampling for analytical testing. Fresh soil subsamples were taken for moisture, LOI, nitrate content, and pH. The results were then statistically analysed (checked for normality, ANOVA, Tukey's post-hoc) to determine whether there was an interaction between kelp additions and earthworm action affecting crop growth.

5.3 Results

5.3.1 Effects of Decomposition Stage of Kelp on Earthworm Feeding Preferences and Soil Properties (Experiment 5.1)

Earthworms increased in mass to a greater extent when provided with decomposed kelp (2 weeks and 4 weeks) as a food source, compared to fresh kelp ($p < 0.05$). Furthermore, the earthworms gained more mass in decomposed kelp (4 weeks) compared to decomposed kelp (2 weeks)(Table 5).

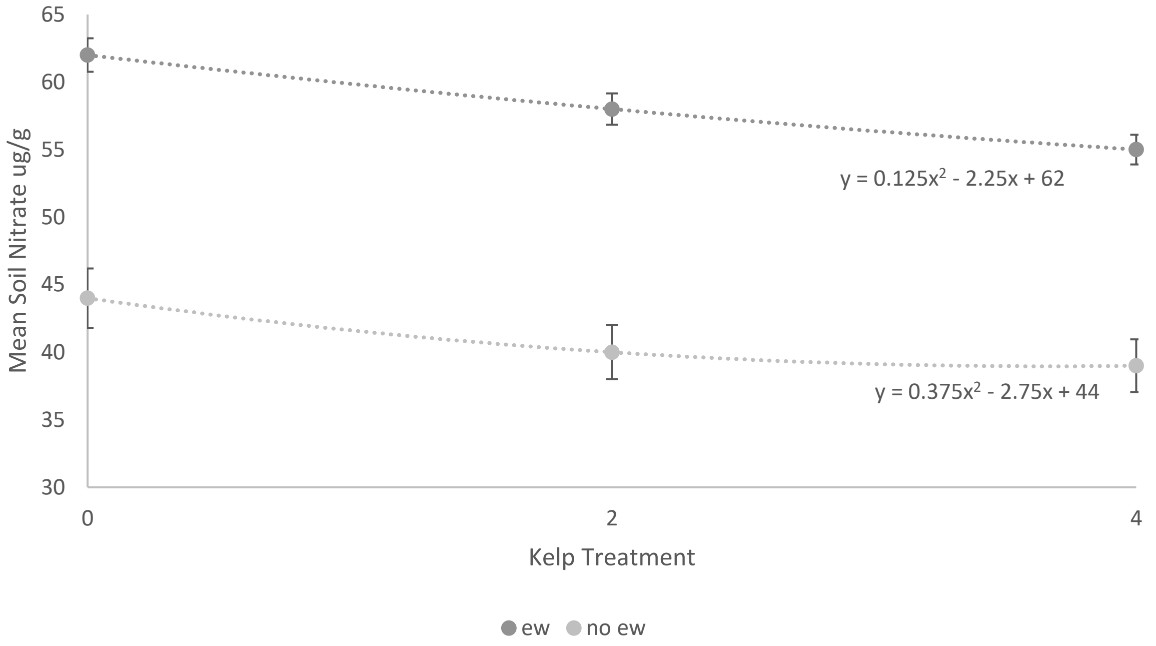
At the first sampling point (4 weeks), and at the second sampling point (8 weeks) there was no difference in pH between the soil in the treatments ($p > 0.05$). Nitrate was greater in mesocosms with earthworms ($p < 0.01$), at both the first and second sampling points (Figure 35). The level of kelp decomposition negatively correlated to soil nitrate ($p < 0.05$) at the first sampling point (4 weeks). At the second sampling point there was no statistically significant relationship between the level of kelp decomposition and soil nitrate ($p > 0.05$). The mesocosm containing the earthworms had significantly higher moisture levels ($p < 0.05$ and $p < 0.01$) at the first and second sampling point respectively, however, moisture levels were unaffected by the level of kelp decomposition ($p > 0.05$). LOI data indicated that the earthworms increased soil organic matter ($p < 0.01$). Further, the level of kelp decomposition was a control on soil organic matter content, with a negative relationship between the level of kelp decomposition and LOI% ($p < 0.01$).

Table 5 Measured soil properties from Experiment 5.1 Effects of the decomposition stage of kelp on earthworm feeding preferences and soil properties. EW = earthworms present, K0 - K4 = level of kelp decomposition in the treatment.

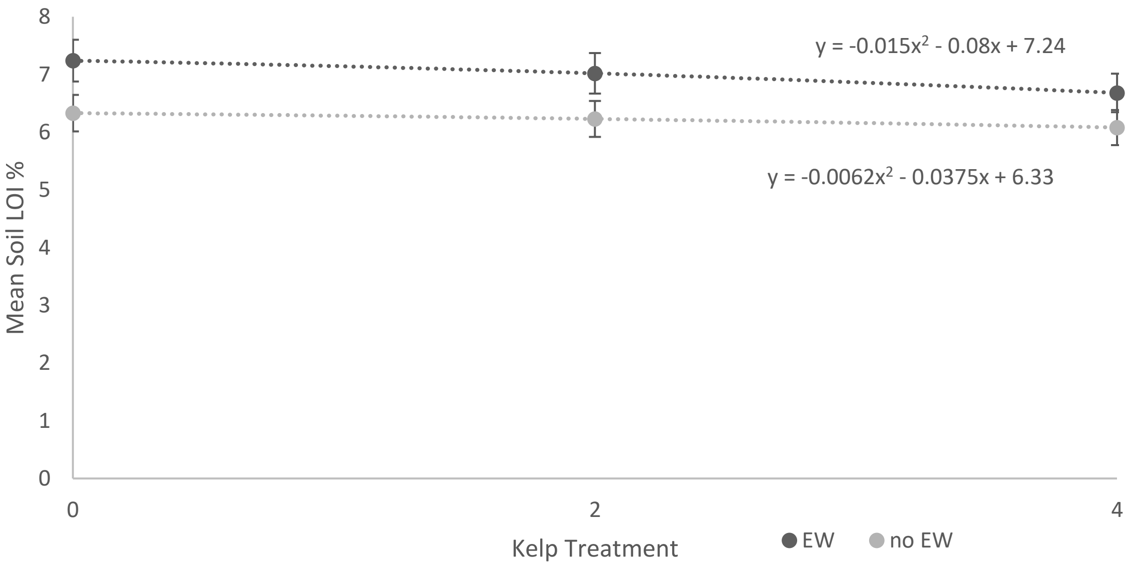
Treatment	**Nitrate ug/g (mean (SD))**		**Moisture % (mean (SD))**		**LOI % (mean (SD))**		**Earthworm mass (g) (fresh weight) change (mean(SD))**
Sampling point (weeks)	*4*	*8*	*4*	*8*	*4*	*8*	*8*
EW Fresh Kelp	62 ± 1.53	60 ± 1.56	20.45 ± 0.78	24.02 ± 1.63	6.79 ± 0.35	7.24 ± 0.68	0.472 ± 0.058
EW Decomposed Kelp (2 weeks)	58 ± 1.98	58 ± 1.78	23.17 ± 1.63	25.38 ± 2.47	6.69 ± 0.15	7.02 ± 0.47	0.637 ± 0.074
EW Decomposed Kelp (4 weeks)	55 ± 1.36	51 ± 3.07	21.83 ± 1.14	26.71 ± 1.50	6.45 ± 0.64	6.68 ± 0.39	0.913 ± 0.091
Fresh Kelp	44 ± 0.98	48 ± 2.29	18.66 ± 2.05	13.24 ± 2.05	6.20 ± 0.37	6.33 ± 0.17	

Decomposed Kelp (2 weeks)	40 ± 2.05	37 ± 1.98	21.18 ± 2.18	15.95 ± 2.18	6.21 ± 1.12	6.23 ± 0.14	-
Decomposed Kelp (4 weeks)	39 ± 3.62	41 ± 2.31	15.20 ± 2.87	21.49 ± 1.81	6.05 ± 0.91	6.08 ± 0.23	-

A


65
60
55
50
45
40
35
30
Mean Soil Nitrate ug/g
0
2
4
Kelp Treatment
y = 0.125x² - 2.25x + 62
y = 0.375x² - 2.75x + 44
ew
no ew

B


8
7
6
5
4
3
2
1
0
Mean Soil LOI %
0
2
4
Kelp Treatment
y = -0.015x² - 0.08x + 7.24
y = -0.0062x² - 0.0375x + 6.33
EW
no EW

C

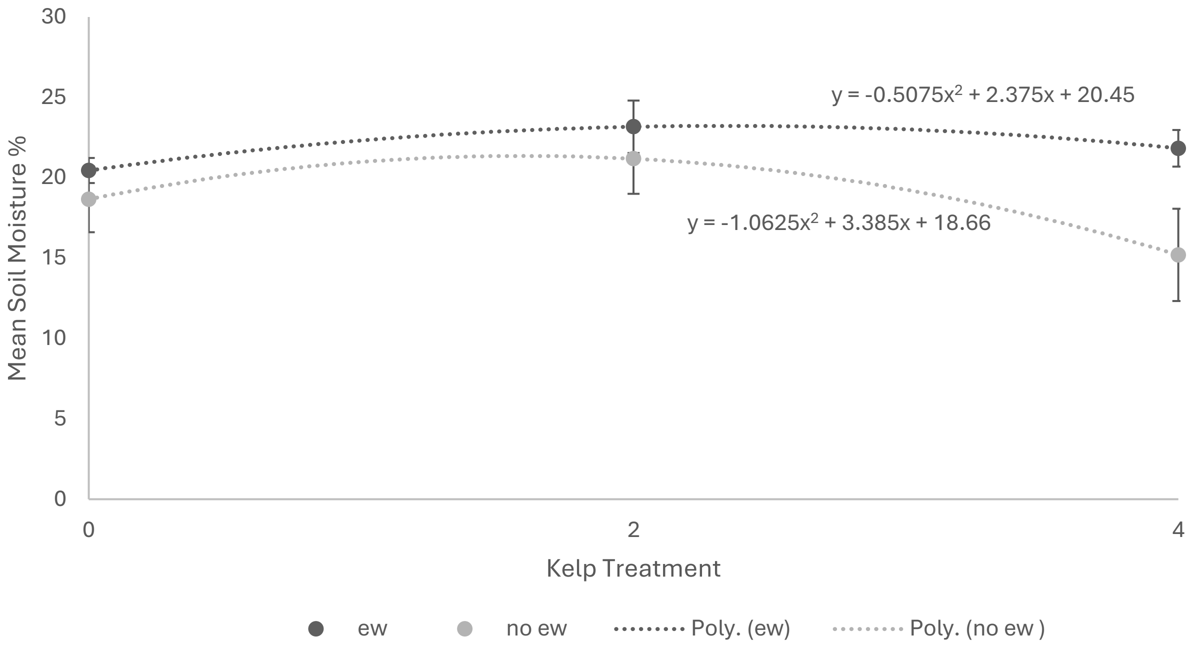


Figure 35 The effect of kelp decomposition treatment (0= fresh kelp 2 = decomposed kelp (2 weeks), 4 = decomposed kelp (4 weeks)) on mean soil nitrate content (ug/g) (A), LOI (B) and soil moisture (C). Error bars indicate SD. n= 30 mesocosms, 5 replicates, 6 treatments. Polynomial trend lines and associated equations are also given.

5.3.2 An Investigation into how the Legacy Effects of Earthworm Food Source (Kelp and Manure) Affects Selected Soil Properties and Plant Growth (Experiment 5.2)

Kelp fertiliser treatment ($p < 0.001$) and the presence of earthworms ($p < 0.01$), and their interactive effects ($p < 0.05$) significantly affected above ground biomass (Figure 36a). Specifically, as the amount of kelp added increased, above ground biomass increased. The highest level of kelp fertiliser treatment increased above ground biomass by six times compared with the no fertiliser control, and the intermediate level of the kelp fertiliser treatment increased above ground biomass by more than double the control. The earthworms reduced above ground biomass in the kelp-fertilised mesocosm, however, there was no difference between the (no fertiliser) control plots for the mesocosms with and without earthworms. The effect of earthworm presence was greatest in the high kelp fertiliser treatment mesocosms, with a reduction in above ground biomass of 53%, in the mesocosm with intermediate levels of kelp additions there was a 33% decrease in above ground biomass. Thus, the legacy effects of earthworms have been found to reduce the impact of kelp on above ground biomass (lettuce crop growth).

Below ground biomass data followed similar trends to the above ground biomass data (Figure 36b). Kelp fertiliser treatment ($p < 0.01$) and the presence of earthworms ($p < 0.01$), and their interactive effects ($p < 0.05$) significantly affected above ground biomass. Specifically, as application rates of kelp fertiliser increased, below ground biomass increased. The highest level of kelp fertiliser treatment increased below ground biomass six times above the no fertiliser control, and the intermediate level of kelp fertiliser treatment increased below ground biomass above the no fertiliser control. The earthworms reduced below ground biomass in the kelp-fertilised mesocosms. The effect of earthworm presence was greatest in the high kelp fertiliser treatment mesocosms, with a reduction in below ground biomass of 47%, in the mesocosm with intermediate levels of kelp additions below ground biomass decreased by 42%. For the no fertiliser control mesocosms, the presence of earthworms increased below ground biomass by 48%. Therefore, this experiment has found that the legacy effect of earthworms negatively impacts crop growth in kelp fertilised systems.

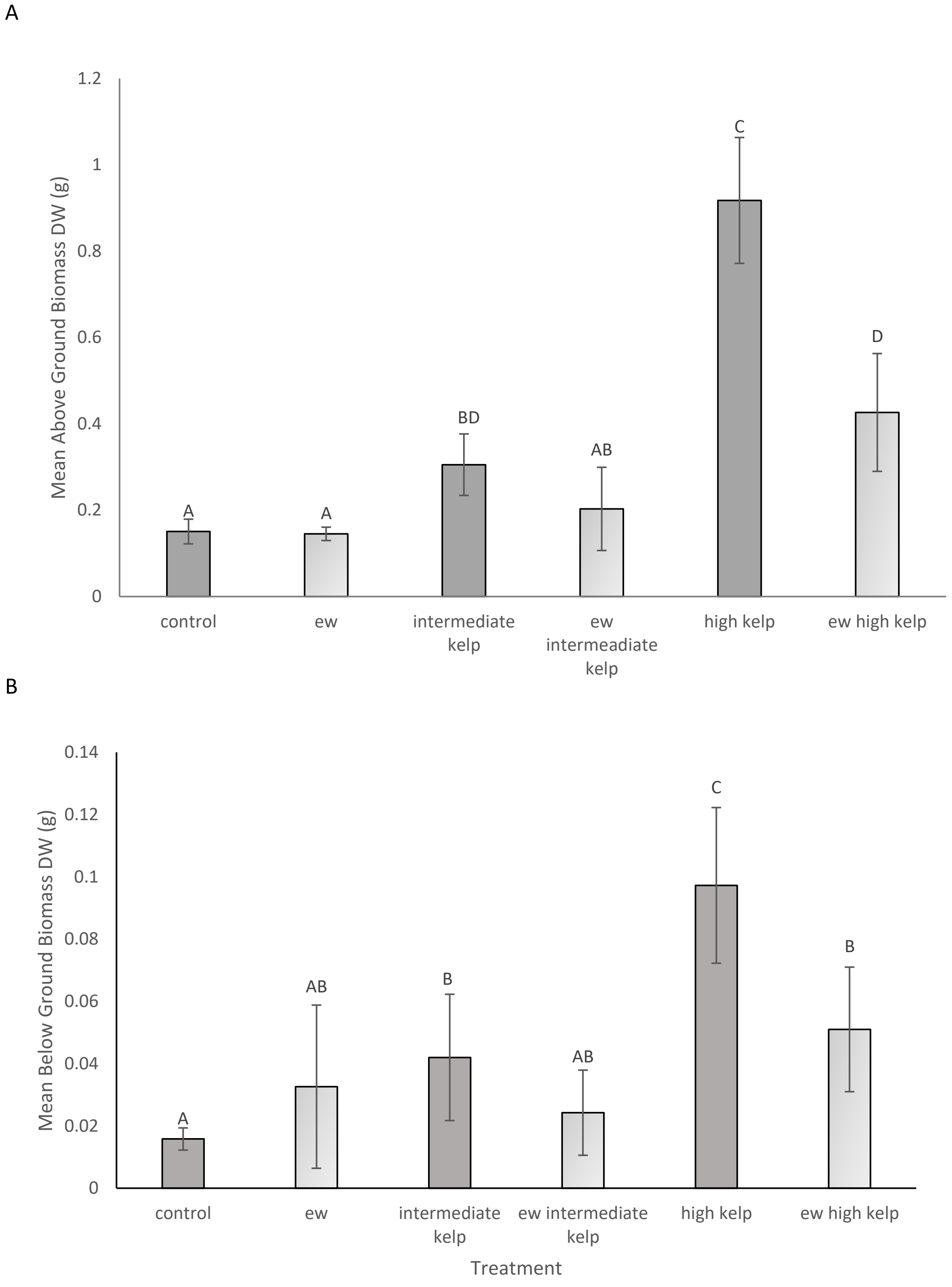


Figure 36 Mean above (A) and below (B) ground biomass (dry weight) of lettuce by fertiliser and earthworm treatment. EW denotes treatments containing earthworms. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 30, 5 replicates, 6 treatments. Error bars represent standard deviation.

Soil nitrate concentrations increased as the level of kelp fertiliser treatment increased ($p < 0.01$) (Table 6). The greatest nitrate concentrations were measured in the high kelp fertiliser mesocosms when earthworms were present in the system. The second highest nitrate concentrations were found in the high kelp addition mesocosm when there were no earthworms present. The lowest nitrate levels were found in the no fertiliser control mesocosms with and without earthworms present. There was no significant difference in nitrate concentrations between the intermediate level mesocosms with and without earthworms present. The effect of earthworms on nitrate concentrations was not significant ($p=0.062$). The interactive effect between kelp and earthworm presence was also not significant ($p > 0.05$).

Table 6 Soil property data for Experiment 5.2

Treatment	Nitrate ug/g (SD)	LOI (SD)
Control	5.48	4.76
Earthworm	5.73	4.99
Intermediate Kelp	13.35	7.13
Intermediate Earthworm	13.28	6.58
High Kelp	23.91	9.77
High Earthworm	38.67	8.62

Soil moisture was partially controlled in this experiment through the use of a gravimetric watering regime (Earl 2003), however, at the time of harvesting it was found that the control mesocoms had significantly lower soil moisture.

Earthworms were found to increase mass when fed on kelp over the 8-week incubation period ($p < 0.01$) (Figure 37). Earthworms in the no additions substrate lost on average 0.7 g. The greater the amount of kelp available for feeding resulted in increased earthworm mass, with the greatest earthworm mass changes observed in the high kelp addition mesocosm.

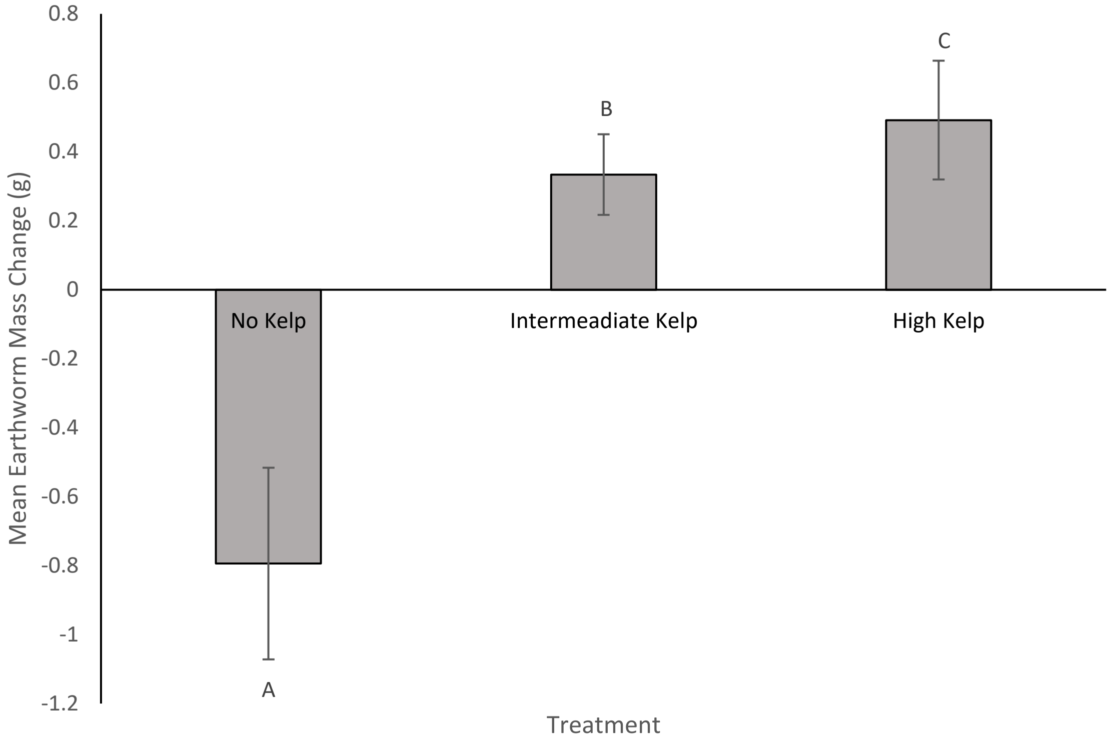


Figure 37 Earthworm mass change by earthworm and kelp treatment. EW denotes treatments where earthworms were present. ANOVA data labels (eg. A/B/C) indicate treatments which significantly differ from other treatments. n= 30, 5 replicates, 6 treatments. Error bars represent standard deviation.

Loss on ignition data, which is a test of the combustible carbon at > 500 °C and in most soils indicates the entire carbon content (excluding inorganic carbonates) indicated that both kelp additions and earthworm presence increased the carbon content of the growing media (Table 6). High kelp additions nearly doubled the LOI%.

5.4 Discussion

Although, there is no direct evidence to show that earthworms consume marine macroalgae, the findings from these experiments indicate that marine macroalgae can support earthworm growth and reproductive cycles. Specifically, it is the gain or maintenance of mass for earthworms in mesocosms where fresh washed kelp was offered as a food source, in comparison to the loss of mass experienced by earthworms in the mesocoms where the kelp was not available that supports this view. However, the mechanisation behind this is yet unclear. Earthworms could be deriving these benefits through the direct consumption of the kelp, or it may be that the earthworms are receiving nutrition indirectly, consuming the byproducts of digestion by soil microorganisms (Lemtiri et al., 2014). Furthermore, consideration should be given to how the feeding behaviour of earthworms may affect the likelihood of the direct or indirect consumption of kelp in the experimental set up. *A. longa* and *L. terrestris* are both anecic (vertical burrowing) earthworms, however, they possess distinct feeding behaviours, with *L terrestris* feeding on fresh plant derived materials on the soil surface and *A. longa* consuming aged plant derived materials already incorporated into the soil (Hoeffner et al., 2022). Both feeding behaviours would, however, likely represent the direct consumption of the macroalgae in this experiment. Further research should assess differences between these anecic species and endogeic species which feed on OM fully incorporated into soil by microbes representing the indirect pathway. The experimental set up used would have facilitated both these feeding behaviours as the kelp was cut up and incorporated in the substrate with part of the kelp remaining at the surface (Bernard et al., 2012). Overall, earthworms (*A. longa, L. terrestris*) increased in mass when kelp (*L. digitata*) was present, and their growth increased when more kelp was available, suggesting that the presence of kelp can directly or indirectly support earthworm growth. Conversely, other studies have shown that earthworm growth is lower when fed marine macroalgae than when fed traditional food sources like horse manure and birch leaves (Butt et al., 2020). The composition of kelp, birch leaves, and horse manure varies significantly, influencing their suitability as food sources for earthworms. Analysis presented in other research of the materials has revealed differences in salt, phenol, and the carbon-to-nitrogen (C:N) ratio.

Kelp, a marine macroalgae, contains higher levels of salts compared to terrestrial sources like birch leaves and horse manure. Generally, kelp contains a significant concentration of salts, primarily composed of various ions, including sodium, potassium, chloride, and others. In *L. digitata*, Na content is around 94.84 ppm, in contrast the Na content is 3.09 ppm and 14.04 ppm for birch leaves and horse manure respectively (Butt et al., 2020). The salt content in kelp may pose a challenge for earthworms, as excessive salt concentrations can affect their growth and overall health. Additionally, the phenol content in kelp is often elevated, potentially creating an unfavourable environment for earthworms. Phenols, known for their antimicrobial properties, may interfere with the earthworm's digestive processes or serve as a deterrent. Phlorotannins, a group of phenols, often account for 10 % dry weight of algae, but in some species, this can be up to 20 % (Ragan & Glombitza, 1986). Contrastingly in birch leaves, the total phenolic content is lower at 6-12 % DW depending on the time of year (Baldwin et al. 1986).

Moreover, the C:N ratio is a critical factor influencing the nutritional quality of organic matter. However, the C:N ratio of kelp (~20:1 from analysis conducted for this Thesis) (17:1) (Butt et al., 2020) is higher than ratios of 6:1 for both horse manure and recently senesced birch leaves (Butt et al., 2020). Earthworms generally thrive on materials with lower C:N ratios, as they provide a more balanced and readily available source of nutrients, thus leading to a selection preference over kelp (Butt et al., 2020).

The higher salt levels might disrupt the osmotic balance in earthworms, affecting their physiological functions (Kou et al., 2024; Seesamut et al., 2022). Additionally, the increased phenol content may have adverse effects on the earthworm's digestive system or microbial communities in their gut (Liebeke et al., 2015). The elevated C:N ratio could contribute to a slower decomposition process, leading to a less favourable food source for earthworms (Dume et al., 2023).

Nitrogen is a key component of earthworm food resources and is essential to produce amino acids (Curry & Schmidt, 2007), which may explain why earthworm growth is lower when fed marine macroalgae with reduced nitrogen content, than when fed on more traditional food stuffs such as manure. The phenol content of marine macroalgae can also reduce their palatability and digestibility. Earthworms prefer low phenol food sources but can adapt to high phenol diets by producing gut surfactants, which requires energy (Liebeke et al., 2015). Without these gut surfactants, earthworms cannot efficiently metabolise high phenol food sources like marine macroalgae. Earthworms are also sensitive to salt, which can reduce the palatability of food sources and damage their dermal layers (Demuynck et al., 2016; Wu et al., 2019). However, despite efforts to remove salt through washing, it is likely that some surface residues of salt would remain, and the internal salt content of macroalgae is known to be higher than that of terrestrial plants (Dring, 1983). This likely resulted in increased salt contents, alongside increased kelp concentrations, yet it did not decrease earthworm fitness in these current experiments. This could be due to the kelp preparation methods (washing to remove surface salt residues amongst particles of shell, sand and other detritus from the blades), which removed large quantities of salt from the food source. The palatability of kelp to earthworms increased with the level of kelp decomposition, likely due to the decomposition process that reduces the highly soluble salt and polyphenol content, making the kelp more palatable to earthworms. Supporting the hypothesis that the stage of decomposition for kelp affects its palatability to earthworms as a food source. Other studies have found that high salinity food sources can negatively impact the quality of compost in a vermicomposting system (Wu et al., 2019). The nitrate content of the compost in the high salinity treatment was 2.3 times lower than in the low salinity treatment (Wu et al. 2019). All of this offers support to the pre-treatment process used in the experiments presented in Chapter 5. The high concentrations of kelp used in the experiments, were of a level, which if left untreated, would have been expected to have a detrimental effect on earthworm fitness, due to excess salt, however, this was not realised. Although similar methods (washing with water to remove salt and debris followed by shearing the kelp) are used in the production of commercially available marine macro-algae fertiliser products, the patented industrial process describes further steps which are not replicated in this thesis, such as acid extraction followed by an alkali digestion, filtration and concentration (patent CN1473798A). This level of industrial processing means that the resulting commercially available fertiliser will likely possess different properties to that of the kelp fertiliser used in these experiments.

These experiments also found that either earthworms or the microbial community stimulated or introduced by the presence played a key role in nutrient cycling in the soil system, which supported crop growth. This is in line with research that suggests earthworms play a critical role either directly or indirectly in nutrient cycling promoting crop growth (van Groenigen et al., 2014). However, the highest level of lettuce growth was observed in the mesocosm with high levels of kelp but no earthworms. This may be because earthworms degrade the kelp (releasing nutrients at an enhanced rate) and plant growth hormones (which rapidly degrade in the soil environment); these mechanisms are hypothesised to be responsible for the observed increase in growth rates from the use of fresh kelp as a fertiliser.

In natural ecosystems, earthworms co-exist with plants, providing a steady source of mobilised plant growth hormones from organic residues (Ahmed & Al-Mutairi, 2022), whereas this experiment sought to examine the legacy effects of earthworms on crop production, meaning that a large proportion of the plant growth hormones released by the actions of earthworms on kelp would likely have been degraded prior to the introduction of the crop to the experiment This is further supported by the finding that, the second-highest growth rates were found in the high kelp earthworm mesocosm, indicating that the earthworms' actions to mobilise nutrients counteracted the reduced effectiveness of plant growth hormones in degraded kelp. In addition, earthworms potentially increased the carbon content of the substrate, as shown by the loss on ignition analysis. Although this experiment was conducted in a controlled laboratory setting with a low nutrient compost, it is likely that the mechanisms at play can be replicated in real-world cropping systems that use kelp as a fertiliser, such as the Lazybed system. However, effects may differ in magnitude due to population densities in the field being lower than that used in laboratory studies.

However, these findings should be interpreted with caution as significant limitations exist in the methodological approach undertaken which includes the use of John Innes composts or Kettering Loam opposed to natural soils. It is likely that the use of alternative medias may impact earthworm behaviour and interactions between kelp and the media. However, due to the remote locality of the field site and the permissions required to abstract soils on mass from the Isle of Rum, it was not possible to transport the required large volumes of natural soil from historically cultivated lazybeds back to the lab/glasshouse for use in experimental purposes.

In conclusion, the experiments presented in this chapter demonstrate the complex relationship between earthworms, kelp and the effect of earthworms on kelp fertiliser in supporting crop through improvements to soil properties. Although, this chapter provides information to add to the existing extremely limited body of research on this topic, knowledge gaps remain and warrant further experimentation. Specifically, this should include a study which examines microbial activity to see whether the earthworms are priming the soil microbial community to break down the kelp or whether the breakdown of kelp and subsequent release of nutrients is primarily mediated by the earthworm community. Further work should also seek to determine whether the legacy effects of earthworms on crop growth in kelp fertilised mesocosms differ from systems with live effects (i.e., earthworms are continuously present in the system).

6. Glasshouse Assessments of Kelp and Manure Fertilisers in Cropping Systems

6.1 Introduction

For an agricultural system to be considered sustainable, it must be able to meet society's present needs without compromising the ability of future generations to meet their own (United Nations, 1988) (see section 2.1 for further details). Soils are a finite cornerstone of agricultural production (Clunes et al., 2022), so if they and their associated functions are degraded or lost, then the ability of future generations to farm that land is diminished. Thus, for an agricultural system to be sustainable the primary concern must be to protect or enhance the soils functionality (Handayani & Hale, 2022). In areas with marginal soils, land management techniques, e.g., the Lazybed system, modified the soil structure enhancing functionality (Darling, 1945). Lazybeds are a type of ridge and furrow agricultural system, which historically was commonly practiced by Scottish island communities and subsistence farmers, however examples can be found across Britain and Ireland (Foster & Smout, 1994) (see section 2.3 for further details). This chapter will refer to Lazybed systems which encompasses the physical structures but also associated management practices e.g., macroalgae use as a fertiliser. It is important to investigate whether the Lazybed system is as susceptible to soil degradation, or whether certain practices were more sustainable compared to aspects of modern conventional arable systems. If they are found to be more sustainable, elements could be taken from the historic system and incorporated in the development of modern agricultural systems to reduce their environmental impact (Butt & Nuutinen, 2021). For example, does the use of kelp, increase soil sustainability, as observed by Blair et al. (2006) in systems using more conventional inputs such as high OM manures as opposed to inorganic fertilisers?

The addition of organic materials to soil to improve crop yields has been practiced for millennia (Bogaard et al., 2013). However, since the advent of the Harber-Bosch process, whereby it became economically viable to produce ammonium on an industrial scale, there has been a shift away from organic-based fertilisers towards inorganic fertilisers (Burrell, 1989; Galloway et al., 2008). Along with other advances in agricultural practices, this has brought about increases in crop yields (Gruber & Galloway, 2008). However, there is a large body of evidence to indicate that long term effects of adding inorganic fertilisers to land is damaging the functioning of the soil and thus its ability to support sustainable crop production (Gregory et al., 2015; Mulvaney et al., 2009). Specifically, adding large quantities of labile plant-available nitrogen (N) to soil, not only feeds the crops but also the soil's microbial population. In a natural system the soil's microbial population is typically dominated by fungi, however, when inorganic fertilisers are added to the system, the opportunistic life strategy of fast-growing bacteria, means that there is a shift in the microbial community composition to bacterial domination (Van Der Heijden et al., 2008). At the same time as utilising the now non-limiting N in the system, organic matter in the soil is used to fuel this growth. This means that organic matter (OM) is rapidly lost from the system as carbon dioxide (CO_2), methane (CH_4) or in water percolating through the soil in the form of dissolved organic carbon or particulate organic carbon (POC), instead of being stored. As organic matter is one of the most important soil components, responsible for holding moisture and nutrients in the soil matrix, increasing plant availability and the nutrient use efficiency of that system, any loss could have deleterious effects on crop yields. Further, the demise of the fungal community in the soil has effects on the soil food web. The strands of mycelium are an important source of food for many micro- and macrofauna, which in turn help cycle nutrients, distribute them throughout the soil profile and aid plant growth. This means that adding inorganic fertilisers to a soil to enhance crop growth can create positive feedbacks, whereby effects on soil functions lead to lower levels of plant growth, and the perceived need to add more inorganic fertiliser to maintain yields (Bardgett & McAlister, 1999; Hijbeek et al., 2016). In addition, the use of inorganic fertilisers has wider environmental impacts such as their high carbon footprint, from the energy intensive production process, mining for potassium and phosphate, and the pollution of water courses (Boer, 2003).

With an increasing recognition of the negative impact of inorganic fertiliser use, there is a need to consider a return to the use of organic fertilisers (see Chapter 2 for further discussion). In addition, since the advent of more intensive agricultural practices, many arable systems operate under a continuous cropping system. Whereas, historically, cropping systems included fallow periods where the soils could recover. The recovery of soils in fallow systems and other systems, which includes rest periods, reduces soil degradation and allows for nutrients to rebuild in the system (Wagner et al., 2023). In many fallow systems, cover crops are planted, or the natural vegetation is left to re-establish to prevent further soil degradation (Blair et al., 2006; García-González et al., 2018; Wagner et al., 2023). Other studies have found that with an increase in the duration that an area of land was left fallow, the values of conductivity, soil organic carbon, available nitrogen, available phosphorus, exchangeable potassium, soil moisture, clay content, and cation exchange capacity of soil increased. Conversely, soil pH and bulk density decreased with fallow duration (Blair et al., 2006). The decrease in bulk density indicates improvements in soil structure and less compaction, potentially as a result of the lack of heavy machinery on the land during the fallow period (Blair et al., 2006). The decrease in pH values under fallow land may be due to higher organic matter input from above-ground biomass and its undisturbed nature (Weil & Brady, 2017). In temperate climates, cover crops and green composts are becoming increasingly common methods to improve soil properties during a non-cropping year or season (Sharratt et al., 2018). This management method controls the negative effects of a lack of vegetation cover, such as the increased risk of soil erosion. Similar in nature to cover crops, leys are areas of land in arable cultivation systems, but are more long-term, remaining in the system for a year or more. Leys are often planted with a variety of nitrogen fixing plants to restore soil health that has been degraded through many years of cropping. Leys are becoming increasingly common in arable systems, and also provide other benefits such as improved soil structure, vegetation buffer zones to ameliorate the effects of pesticide application to crops, and biodiversity and pollinators (Goulson et al., 2010; Toivonen et al., 2022).

A challenge in a short-term research project is to assess the sustainability of the multi-year rotating to fallow system, traditionally employed for Lazybed systems, within a given timeframe. This issue has been addressed in this chapter by undertaking experiments in controlled environmental conditions for optimal growth, with crops grown in continuous cultivation. This approach was used to test different rotation systems and how ecosystem functions were impacted when coupled with the different fertiliser treatments. While employing a continuous cultivation in controlled conditions approach can offer various advantages during experimentation, it is crucial to acknowledge the disbenefits of this experimental approach which does not wholly mimic natural processes. Specifically, soils require rest periods outside the growing season. This period is essential for soil regeneration and maintaining its overall functionality. Moreover, certain groups/species of soil fauna exhibit growth and reproductive cycles that align with specific temperature requirements (Bokhorst et al., 2012). Implementing continuous cultivation practices in controlled experimental conditions may interfere with these natural processes, hindering the growth, reproduction and development of soil fauna communities which play a pivotal role in soil nutrient cycling. For optimal soil functioning to support crop growth, it is imperative to allow these organisms the necessary time and conditions to complete their life cycles, contributing to the overall biodiversity and functionality of the soil ecosystem. Additionally, the germination of seeds is often influenced by temperature variations. Some seeds require exposure to cold temperatures (stratification) for a specific duration to break dormancy and initiate germination (Klupczyńska & Pawłowski, 2021). By exclusively focusing on warmer seasons or neglecting the importance of cold periods, continuous cultivation in controlled environmental conditions may inadvertently limit the successful germination of certain crops. This limitation can impede overall crop productivity and lead to suboptimal yields. This chapter (detailing Experiment 6.1) tests different management systems of continuous cropping and 1 growing season fallow, against different fertiliser applications (kelp, manure, kelp-manure).

Aim: To understand how kelp-manure fertilisers and cropping systems (alternate (rotations with rest periods) and continuous) affect crop yields and soil properties over four growing seasons.

Objective 1: To measure effects of the addition of mixed kelp+manure fertilisers over 4 growth cycles will change soil properties and crop yields.

Objective 2: To determine effects of continuous cropping systems and alternate cropping systems on crop yields and soil properties.

Objective 3: To assess effects of the addition of mixed kelp-manure fertilisers on soil properties and crop yields in alternate versus continuous cropping systems.

To address the aim and objectives the following hypothesis was devised:

Experiment 6.1

There are differences in soil properties and crop yields between cropping systems and fertiliser treatments, and that these variables will be affected by the interaction between cropping system and fertiliser treatment.

6.2 Methods (Experiment 6.1)

A fully factorial experiment was conducted to test how the use of kelp and manure fertilisers affected soil properties and crop yields in continuous and alternate cropping systems.

The kelp was processed as described in 3.5. The kelp was then stored at -20 °C until the start of each new experimental growing season, after which it was defrosted and cut into approximately 2 cm^2 pieces. This was to ensure that the kelp used across the four growing periods was homogenous, as the properties of fresh kelp change seasonally (Sheppard et al., 2023). Freezing at -20 °C would greatly reduce the degradation of plant growth hormones known to be present high concentrations (Neubig et al., 2014) in fresh kelp, -80 °C is standard for the storage of samples for hormone analysis which requires a greater degree of preservation (Wang et al., 2020), however, for this experiment this degree of sample preservation was not required. Manure (derived from cattle excrement) was sourced from B&Q (Good Home, Peat-free Beds & Borders Manure 50L) at the start of the experiment and stored at -20 °C until the start of each new experimental growing season, after which it was defrosted and broken up prior to application. This also in part standardised the pre-treatment of the fertilisers prior to application. The kelp and manure also were tested for total N content, which was then used to determine the quantity of kelp and manure to be added for each fertiliser treatment, to standardise the nitrogen (N) content of the fertiliser treatments. The total N content per dry weight (dw) of the kelp and manure was 2.5% and 5.0% respectively, with relative fresh moisture contents of 58.7% and 60.1%, respectively. Using the kelp and manure three experimental fertiliser treatments, plus a control with no additions were created. Specifically, kelp and manure were applied to the mesocoms in the following quantities to create the four fertiliser treatments:- Kelp (100g); Manure (50g); Kelp+manure (50g+25g); Control (0).

Furthermore, cropping system treatments were tested in this experimental set up. The cropping system treatments, including alternate and continuous, are outlined below, with the growing season defined in this chapter as the two-month period anticipated for crop growth prior to harvesting.

1. Continuous (four successive harvests).

2. Alternate (two fallow (growing period 1 and 3) and two harvests (growing period 2 and 4) in four growing periods).

The experimental treatments and labelling system are detailed in Table 7.

Table 7 The mesocosm fertiliser and cropping system treatments and labelling system used in this experiment. ✓ indicates when a crop was sown, ✗ indicates fallow mesocosm.

			Growing period			
Fertiliser Treatment	**Cropping System**	**Replicates**	**1 May-July**	**2 July-September**	**3 September-November**	**4 November-January**
Manure	Continuous	5	✓	✓	✓	✓
Manure	Alternate	5	✗	✓	✗	✓
Kelp+manure	Continuous	5	✓	✓	✓	✓
Kelp+manure	Alternate	5	✗	✓	✗	✓
Kelp	Continuous	5	✓	✓	✓	✓
Kelp	Alternate	5	✗	✓	✗	✓
Control	Continuous	5	✓	✓	✓	✓
Control	Alternate	5	✗	✓	✗	✓

Mesocosms were set up by placing a layer of mesh (1 mm aperture) at the base of a 12 L pot (Tall Heavy Duty Container Pots, 12L, LBS), with a 3 cm layer of gravel (10 mm gravel), then 11 L of John Innes No.1 compost added. John Innes No. 1 was selected as mesocosm substrate due to a relatively low nutrient content, and homogenous structure. John Innes composts are extensively used in research, with the no.1 standard used in this experiment as this compost has the lowest nitrogen, phosphorus and potassium contents of the three standard compost available (Bunt, 1963). This was to try and replicate the expected nutrient conditions in marginal soils such as the Isle of Rum, where the Lazybed system was historically practiced in part due to the low nutrient levels. Macronutrient contents for John Innes no.1 are as follows N 5.1%, P 3.2% and K 8.1%) (Bunt, 1963), these are comparable with medium-low soil nutrient contents (PDA, 2024), but due to the small size of the pots used in experiments coupled with the watering regime, it is likely that these nutrients are rapidly lost, leaving the compost in a low nutrient state. At this stage, the mesocosms were watered repeatedly over the course of 24 hours, to obtain substrate with a moisture level desirable for crop growth. The mesocosms were labelled and the fertiliser treatments applied manually, by incorporating the kelp and manure fertilisers into the top 5 cm of the mesocosm with a trowel. Eight spring onion seeds (Onion, Spring- Performer, Johnsons) were planted in each of the continuous cropping mesocosms, with the alternate mesocosm left fallow for the first growing period. Spring onions were chosen as the experimental crop in this chapter due to their rapid growth thereby shortening the length of the experiment and allowing for growth to be assessed over a greater number of continuous cultivation periods. The mesocosms were placed in individual drip trays and installed in a glasshouse at Myerscough College, UK (Figure 38). An automatic watering system (Hozelock) provided two minutes of watering per day at sunrise. During warm periods, when ambient temperatures exceeded 23 ^{o}C, the watering level was adjusted to water for an extra two minutes at sunset. Any weeds were removed manually from the mesocosms as they appeared and after two weeks the spring onions were thinned to leave four individual plants per mesocosm (Figure 39).

Figure 38 The experimental set up in the Myerscough glasshouse for Experiment 6.1 investigating the effect of fertiliser type and cropping system on the growth of spring onions over four consecutive growing periods. Treatments were arranged in columns which were rotated (along the x and y axis of the set up) throughout the duration of the experiment.

Figure 39 Four spring onion plants after thinning in the early growth stages in Experiment 6.1 which aimed to investigate the effect of fertiliser type and cropping system on the growth of spring onions over four consecutive growing periods.

After 2 months, the spring onions were harvested, and a subsample of soil (approximately 50 g) taken from each mesocosm (Figure 40). Fertiliser treatments were then reapplied, and spring onion seeds replanted as determined by the experimental treatments. This process was repeated over four x two month growing periods, starting in May 2021, and ending in January 2022 (as detailed in Table 7).

To assess the crop yields of each treatment, harvested spring onions were prepared by trimming off any remaining root biomass (the majority of the root biomass detached from the spring onions as they were lifted from the mesocosms), then removing any soil by submerging the root in clean water and washing by hand. Each individual spring onion was weighed. Mesocosm and treatment totals for spring onion biomass and means were calculated. Below ground biomass was not calculated in order to minimise disturbance to the mesocosms through collection.

Figure 40 Experiment 6.1 during the second harvest.

Soil samples ~50 g, collected by hand using a trowel from the top 5 cm of each mesocosm at the end of growing period 4 tested for moisture and carbon content, pH and nitrate. These sub-samples were first passed through a 2 mm sieve, oven-dried at 105 ^{o}C until a constant mass was reached, then placed in a furnace at 535 ^{o}C for four hours to determine moisture content and loss on ignition (LOI) respectively. The pH was determined by adding 5 g +/- 0.1 g of substrate to a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), plus 25 ml of DI water, shaken by hand for 1 minute at 10-minute intervals for 30 minutes, then the liquid phase filtered through Whatman no. 1 and measured using a Hanna Edge probe (Barillot et al., 2012). To assess nitrate, 5 g +/- 0.1 g of substrate was put into a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), and shaken and inverted by hand for two hours and filtered through Whatman no. 1 and analysed on a Nitrachek 404 Meter + Test strips Kit (KPG Products Ltd) (Kang et al., 2005).

6.2.1 Statistical Analysis

All data were statistically analysed using SPSS. One way ANOVA with Tukey's multiple comparison post hoc tests were conducted to test for effects of fertiliser treatments and cropping system (alternate vs continuous) on soil properties and crop yields; p values < 0.05 were deemed significant. It was assumed that all data entered into the ANOVA was normally distributed: prior to running the ANOVA analyses data were checked for normality using a visual assessment of QQ plots and Shapiro-Wilk test of the statistical significance of normal distribution. It was also assumed that the distributions have the same variance, and that the data are independent.

6.3 Results (Experiment 6.1)

6.3.1 Growing Period 1

The kelp+manure fertiliser treatment had significantly lower yields than the other three fertiliser treatments including the control (Figure 41). The ratio between the treatment to the control is also shown in Table 8 for growing period 1. The statistical analysis revealed that fertiliser treatment did affect crop yields ($p < 0.05$).

Table 8 The ratio of the continuous control biomass to the treatment biomasses.

	Ratio of the treatment to control			
Treatment	*GP1*	*GP2*	*GP3*	*GP4*
Manure continuous	1.03	1.77	2.15	1.36
Manure alternate		1.98		2.10
Kelp-manure continuous	0.61	1.51	2.23	1.89
Kelp-manure alternate		1.83		2.03
Kelp continuous	0.96	1.68	2.40	2.20
Kelp alternate		1.87		3.40
Control continuous	1	1	1	1
Control alternate		1.60		0.95

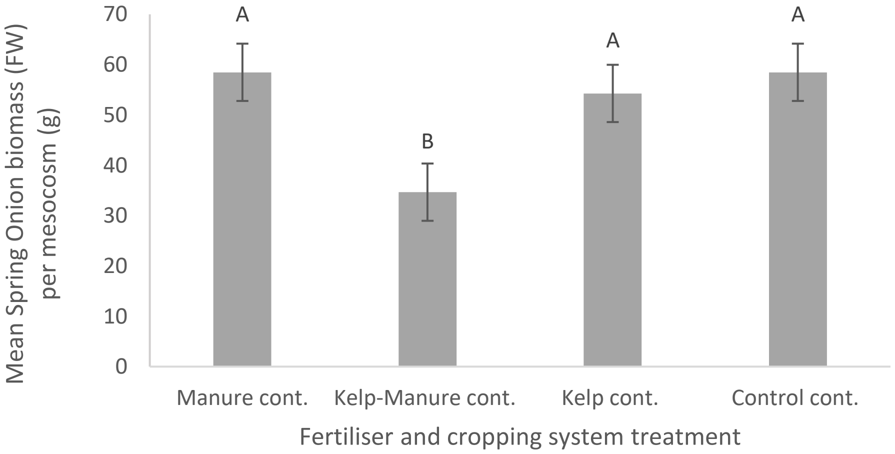


Figure 41 Mean spring onion above ground biomass, in continuous cropping mesocosms after Growing Period 1 (T1), by fertiliser treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 20, 5 replicates, 4 fertiliser treatments. Error bars represent standard deviation. FW= fresh weight. Cont. = continuous, Alt. = alternative cropping regime.

6.3.2 Growing Period 2

This was the first harvest where all mesocosms had an active growing period. Cropping system (alternate or continuous) was found to have a significant effect on spring onion biomass ($p < 0.01$) (Figure 42). The lowest crop yields were observed in the control continuous system, whereas the highest yields were in the manure alternate, kelp alternate and kelp+manure alternate treatments. Fertiliser treatment had statistically significant effects on crop yields ($p < 0.001$). The cropping system of continuous vs alternate had statistically significant effects on crop yields ($p < 0.01$). There was a statistically significant interaction between cropping system and fertiliser treatments ($p < 0.05$). With the effect of cropping system greatest in the control fertiliser treatment. The ratio between the treatment to the control is also shown in Table 8 for growing period 2.

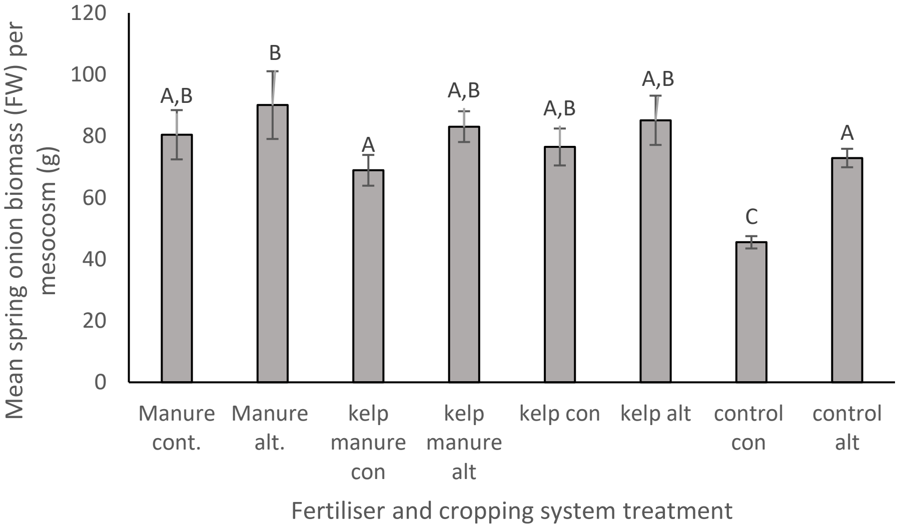


Figure 42 Mean spring onion above ground biomass per mesocosms after Growing Period 2 (T2), by fertiliser and cropping system treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments. Error bars represent standard deviation. FW= fresh weight.

6.2.3 Growing Period 3

Fertiliser treatment significantly affected spring onion yields in growing period 3 ($p < 0.001$) (Figure 43). The highest yield, observed in a kelp-fertilised mesocosm was 2.41 times greater than yields in the control. Post hoc testing revealed that the yields for all fertilised treatments did not differ significantly from each other ($p > 0.05$). The ratio between the treatment to the control is also shown in Table 8 for growing period 3.

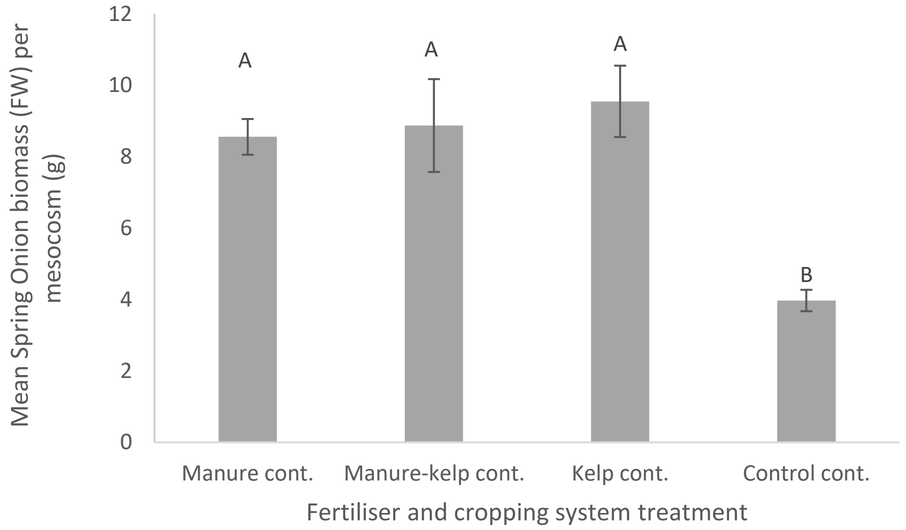


Figure 43 Mean spring onion yields (biomass (g)) per treatment mesocosms for Growing Period 3 (T3). Spring onion above ground biomass in continuous cropping mesocosms after Growing Period 3 (T3), by fertiliser treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 20, 5 replicates, 4 fertiliser treatments. Error bars represent standard deviation. FW= fresh weight.

6.3.4 Growing Period 4

Kelp fertilisers resulted in the greatest yields in the alternate system. There was a significant difference in yields between the alternate and continuous cropping system in kelp-fertilised mesocosms; for manure-fertilised mesocosm the effect of continuous vs. alternate cropping systems was reduced. However, for the kelp+manure and control fertilisers there was no difference in yields between the alternate and continuous cropping system after four growing periods. Fertiliser type ($p < 0.0001$) and cropping system ($p < 0.01$) significantly affected spring onion yields in growing period 4 (Figure 44).

Further, there was a significant interaction between fertiliser type and cropping system ($p < 0.01$). There were strong effects of growing period on yields. This was due to the conditions in the glasshouse being semi controlled and ineffective and maintaining temperatures and sufficient light levels through winter. The ratio between the treatment to the control is also shown in Table 8 for growing period 1.

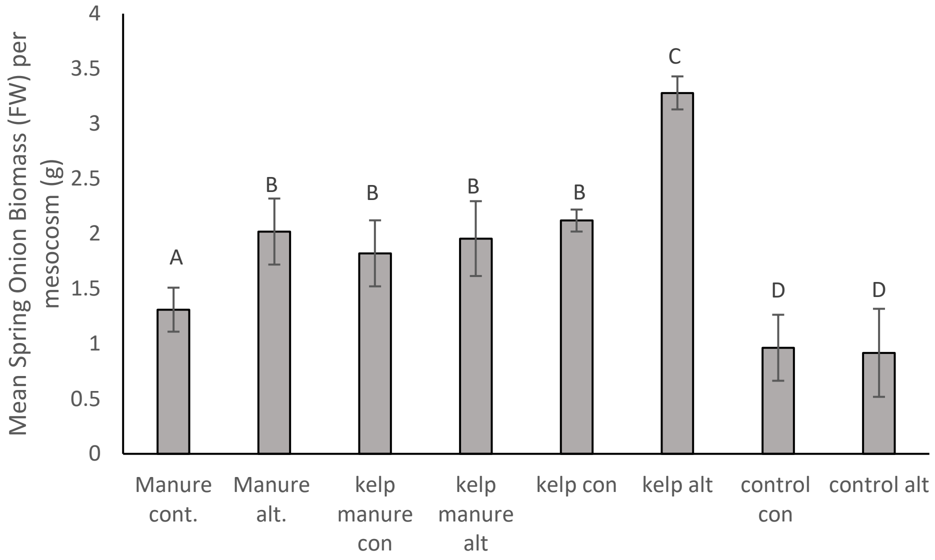


Figure 44 Mean spring onion above ground biomass per mesocosms after Growing Period 4 (T4), by fertiliser and cropping system treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments. Error bars represent standard deviation. FW= fresh weight.

Loss on ignition gives an indication of the organic matter content of the soil and results from the fourth harvest (T4) indicated that organic carbon content was affected by fertiliser type ($p < 0.001$) and cropping system ($p < 0.01$) (Figure 45). Kelp fertilisers had significantly greater LOI results than the control. Manure fertilisers resulted in the second greatest rise in LOI. However, there was no difference in LOI values between the soil from the control and the kelp+manure treatments. Alternative cropping systems had greater LOI results than the continuous cropping system. The greatest difference between continuous and alternative cropping systems was observed in those under the kelp fertiliser application treatment, followed by the manure fertiliser treatment. There was no significant difference in LOI for the different cropping regimes in the kelp+manure and the control fertiliser treatments (p > 0.05).

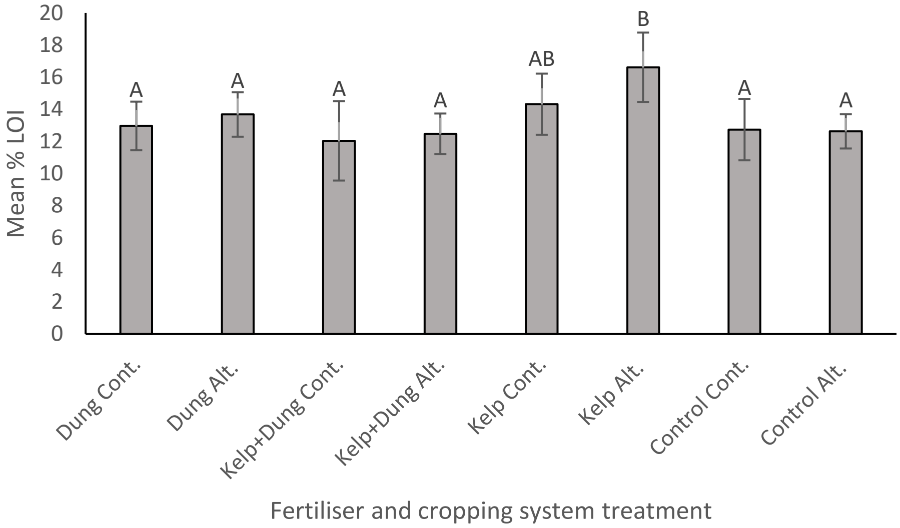


Figure 45 Mean LOI% after growing period 4 (T4), by fertiliser and cropping system treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments. Error bars represent standard deviation.

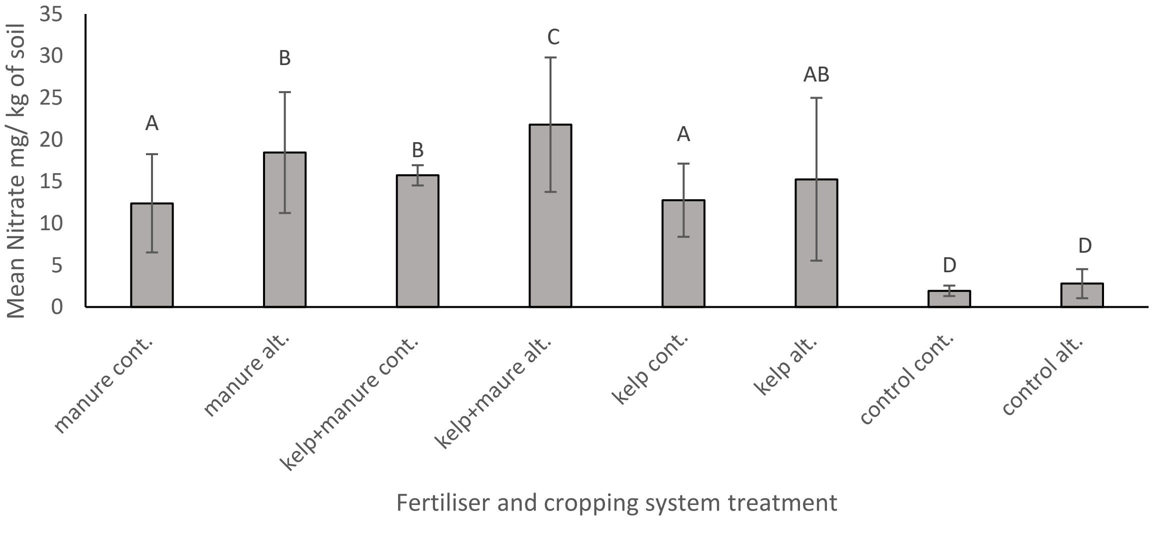


Figure 46 Mean nitrate levels in soil (mg NO_3-/ kg soil (FW)) after growing period 4 (T4), by fertiliser and cropping system treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments. Error bars represent standard deviation.

After four growing periods soil nitrate levels varied by treatment ($p < 0.001$) and cropping system ($p < 0.01$) (Figure 46). The levels observed in the control treatments were much lower than the mesocosms with the kelp, manure, and kelp+manure treatments. There was no significant difference between soil nitrate levels for the mesocosm treated with manure, kelp+manure and kelp ($p > 0.05$).

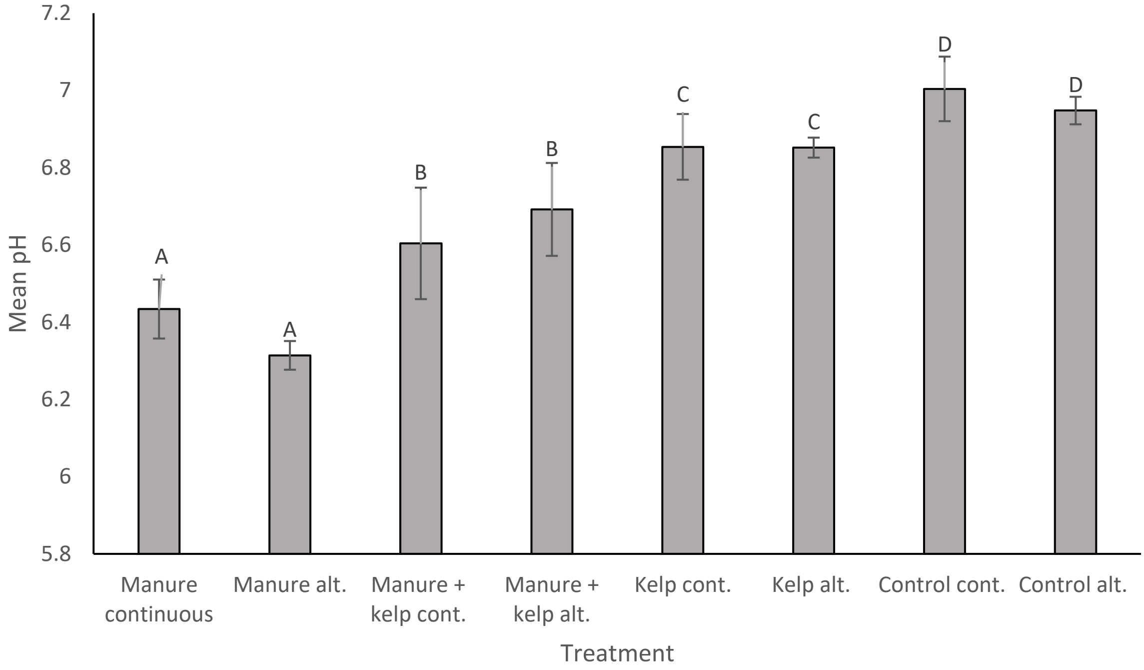


Figure 47 Mean soil pH after growing period 4 (T4), by fertiliser and cropping system treatment. ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments. Error bars represent standard deviation.

Soil pH was significantly affected by fertiliser treatment ($p < 0.01$) (Figure 47). The manure fertiliser treatment resulted in the greatest decrease in soil pH from the no additions control, followed by manure + kelp, and kelp. Cropping system did not significantly affect soil pH.

6.3.5 Temporal Comparisons of Yield

A comparison of the yields in harvest 1 (T1) and harvest 2 (T2) for the continuous cropping treatments, revealed how all three fertiliser treatments (manure, kelp+manure or kelp) increased spring onion wet weights, whereas crop yields where no fertiliser was used in the control treatment were lower (Figure

48). The largest difference in yields between harvest 1 and 2 was found in the kelp+manure treatment. Kelp+manure had consistently lower yields than manure and kelp fertiliser treatments, however, in harvest 2 the increase in yields for kelp+manure were far greater than the increase in yields for manure and kelp. Due to the large effect of growing period, this analysis has not been repeated tracking differences for growing period 3 and growing period 4, instead the analysis of growing period 1 and growing period 2 should be seen as standalone as during these periods, conditions were sufficient to support growth.

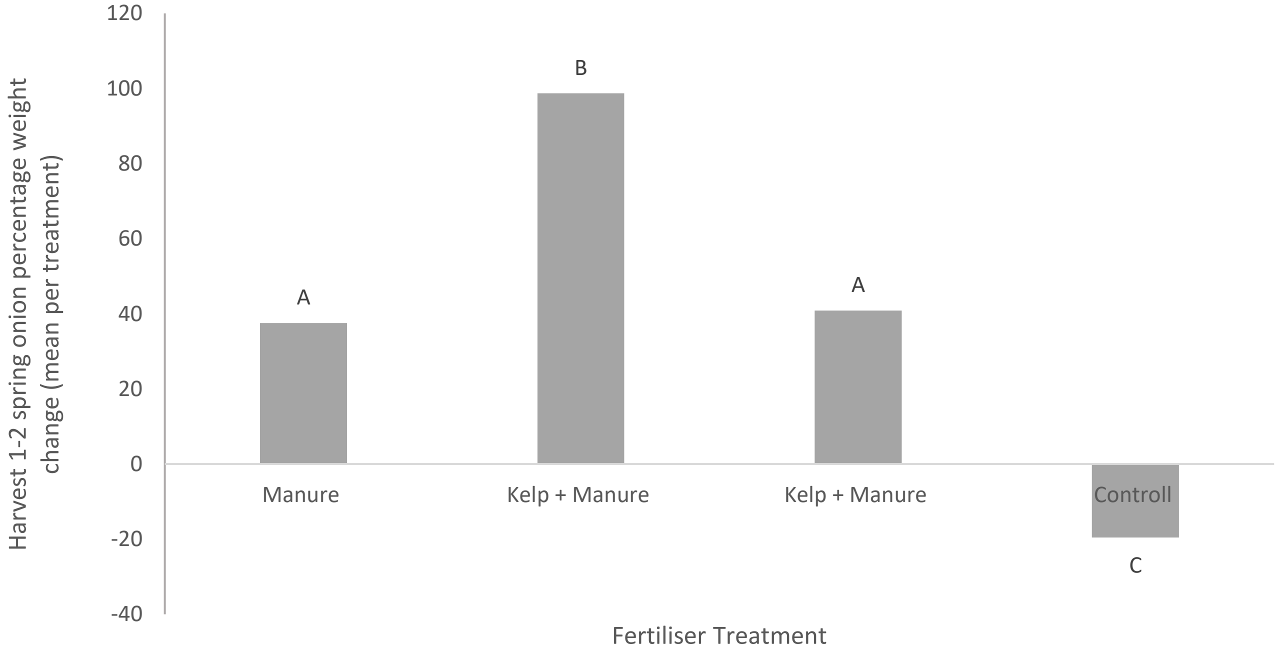


Figure 48 The difference in mean spring onion above ground biomass s by fertiliser treatment between Growing Period 1 1 (T1) and Growing Period 2 (T2). ANOVA data labels indicate treatments which significantly differ from other treatments. n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments.

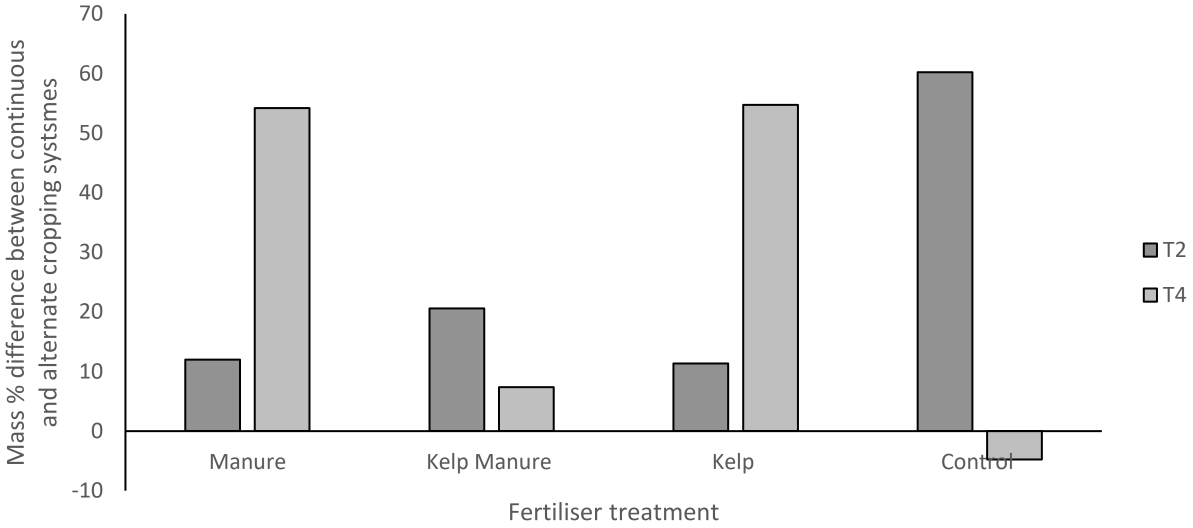


Figure 49 The difference in mean spring onion above ground biomass s by fertiliser and cropping system treatment in Growing Period 2 (T2) and Growing Period 4 (T4). n= 40, 5 replicates, 4 fertiliser treatments, 2 cropping system treatments.

The difference in yields between continuous and alternative systems during growing period 2 and growing period 4 is displayed in Figure 49. The data was analysed as percentage difference in yield due to changes in abiotic factors in the glasshouse during the experiment. The effects of manure and kelp fertiliser treatments are similar, with a substantial increase in the relative difference between the continuous and alternate cropping systems between growing period 2 and growing period 4. Whereas for the kelp-manure treatment, the difference between continuous and alternate cropping systems was lower in growing period 4 than in growing period 2. Differences in spring onion mass (%) in growing period 4 were similar for kelp and manure fertilisers.

6.4 Discussion

The main findings of this chapter demonstrated how the use of kelp over four growing periods resulted in greater yields in low nutrient systems alongside improvements to key soil properties such as soil organic matter content (indicating that outputs can be maintained in this system) and that the use of kelp as a fertiliser in conjunction with an alternate (1 growing period fallow) cropping system, further increased yields.

The LOI results indicated that the use of kelp or manure fertiliser increased soil organic matter content, after four growing periods, by comparison with control and the kelp+manure mixed fertiliser. It is unclear as to why the co-application of kelp and manure did not increase LOI values above the control as with the singular kelp and manure applications as approximately the same amount of OM was added to the pots for all of the three active (non-control) fertiliser treatments. This could be that the individual microbial communities, naturally found on the kelp and manure, were able to respond rapidly to decompose and/or metabolise the new input of organic matter, increasing the organic matter which was lost from the system as CO_2, dissolved organic carbon or particulate organic carbon (Khan et al., 2007). Although the kelp was extensively washed prior to application, it is likely that this process would not have been sufficient to sterilise the kelp, and the microbial community would have persisted to some extent. Whereas, in the single source fertiliser mesocosms it is possible that the microbial community, metabolised the fertiliser OM at a slower rate, one possible mechanism for this would be through fungal dominated pathways, to retain more of the OM in the system (Crawford et al., 2012; Hijbeek et al., 2016). Studies have found that kelp applications increased microbial respiration in sandy soils (Haslam & Hopkins, 1996), which also led to improvements in soil structure. This contrasts to the compost substrate used in this experimental set up (Experiment 6.1). However, interestingly, their study recorded greater microbial activity in the soil with the lower kelp addition, (7.53 nmol CO_2 g^{-1} soil hr $^{-1}$) compared to the higher kelp additions (6.84 nmol CO_2 g^{-1} soil hr $^{-1}$), however this was still far greater than the control treatment with no kelp additions, with a respiration rate of 1.42 nmol CO_2 g^{-1} soil hr $^{-1}$ (Haslam & Hopkins, 1996). This is interesting as the current experiment found that OM was lower in the lower level of kelp additions, which had been added with manure, suggesting that microbial activity was greater than in the mesocosm where a greater level of kelp was added. This could be due to the higher levels of kelp additions reducing the rate of microbial activity potentially due to elevated concentrations of phlorotannins, which are known to possess antimicrobial properties (Eom et al., 2012).

The level of OM In soil is an important factor to determine the overall sustainability of agroecosystems (Altieri et al., 2015) such as Lazybeds and draw comparisons on the relative sustainability of the Lazybed system compared to other systems. OM in soils acts as a sponge to hold water and increase the soils cation exchange capacity (Costantini et al., 2018; Quastel & Webley, 1947). Cation exchange capacity is a property of soils which retains cations such as potassium, magnesium, calcium and ammonium, increasing the soils nutrient status (Sparks, 1995). Through binding these positively charged cations to the negatively charged particles in the OM, there is a reduction in the levels of nutrients lost from the soil through water transport (Lavallee & Cotrufo, 2020). Further, as OM decomposes, it releases the nutrients bound at cation exchange sites and nutrients in the body of the OM (Lavallee & Cotrufo, 2020). The rate of OM decomposition is determined by a range of biotic and abiotic factors, such as action of soil mesofauna and temperature (Prescott & Vesterdal, 2021). Excess nutrients applied to land in the form of inorganic fertilisers rapidly increase the rate of OM decomposition (Fornara et al., 2020). However, under most circumstances the rate of organic matter decomposition in temperate climates is at a supressed rate, which allows for the steady release of nutrients throughout the growing period, ensuring that the plant community has access to the nutrients it needs for healthy growth and reproduction (Mayer et al., 2020). The level of OM in soils is highly influenced by a range of land management factors in addition to the use of fertilisers. Specifically, the level of physical soil disturbance is a key factor in determining the level of SOM (Haddaway et al., 2017). Studies have found that in no-till systems the levels of OM increase compared to tilled cropping systems (Blair et al., 2006). This study found further evidence to support this, with ley periods (alternate cropping) found to increase soil LOI values and yields in mesocosms where leys periods were used alongside kelp applications. The LOI values found in this study across all treatments are above those which would typically be present in in arable systems (where LOI of 8.8% would be considered high) (NRM, 2024), however, this experiment was conducted under glasshouse conditions, so the LOI values are not directly comparable to field settings.

The data presented here (Chapter 6), showed that the rate of OM addition must be greater than the rate of OM decomposition as the level of OM in the soil increased over the four growing periods compared with the no additions control. This indicated that as the OM can be increased (a key property of soil health), the system can continue under this management system in perpetuity without negative impacts on functions such as yields. This, by definition, makes the farming system sustainable (Clunes et al., 2022).

The source of OM input is critical to determine how the OM breaks down in the soil and how much is stored (Lavallee & Cotrufo, 2020). When inputs are “foreign” to the ecosystem, as with the application of kelp to Lazybeds, the fauna are likely to be less adapted to breakdown the input and OM builds in the soil at a greater rate (van der Wal & de Boer, 2017). This could explain why the addition of kelp fertiliser resulted in the greatest LOI results after 4 growing periods. Additionally, the reasons for the enhanced build-up of OM in the system could be due to changes in the soil physical and chemical properties induced by the addition of kelp. For example, alginate in kelp acts to bind soil aggregates; larger soil aggregates are associated with increased levels of soil OM (Lado et al., 2004). Alginate also holds water in the soil increasing soil moisture content as observed in this experiment (Quastel & Webley, 1947). It is widely recognised that OM build up is greater in more moist soil conditions; extreme examples of this can be observed in peat bogs (Freeman et al., 2001). Further, soil pH increased from the addition of kelp over that of when manure was used as a fertiliser. pH tends to fall naturally over time in cropping systems and can be further exacerbated by the use of fertilisers (Zhu et al., 2023). This is due to the hydrogen ions being produced either through the input of organic acids associated with the fertilisers or the release of hydrogen ions from plant roots as a byproduct of nitrification (Msimbira & Smith, 2020). This aligns with the finding in this experiment that the control mesocosm with much lower growth and no fertilisers added had a higher pH. It should be noted that due to the timescales involved in this experiment, seasonal variability in fertiliser properties and the kelp collection process, the kelp and manure were frozen prior to use. Freezing organic materials such as kelp can significantly influence their decomposability upon defrosting (Akomea-Frempong et al., 2021). When organic matter undergoes freezing, the low temperatures slow down microbial activity and enzymatic processes responsible for decomposition (Byun et al., 2021). This temporary halt in the decay process preserves the organic material, however, once the organic materials are thawed, microbial and enzymatic activities resume at an increased rate (Bevan *et al*., 1997). The freezing and thawing process can lead to the release of nutrients as the water inside the organic material expands breaking cell walls, making the material more readily available for decomposition by microorganisms (Pastore et al., 2023).

Results presented here (Chapter 6), demonstrated that yields in alternative cropping systems outperformed continuous cropping systems. The act of cropping (removal of the plant biomass and disturbance of the soil) disturbs the soil and removes nutrients and organic matter from the system (Nandan et al., 2019). When an alternate cropping system is employed, the system is given a chance to recover from the cropping disturbance (Haddaway et al., 2017). Further, the increase in OM and associated nutrient and water storage capacity, build resilience in the system, and over time the disturbance caused by cropping is reduced. Building resilience in cropping systems is crucial for their long-term sustainability. An alternate cropping system is more resilient to pests and diseases and extreme weather conditions (Knox et al., 2011; Lamichhane et al., 2015). For example, the increase in soil OM associated with alternate cropping systems, helps retain moisture in the soil for longer periods, thus in times of low rainfall the soil provides a source of water for the crop (Zhao et al., 2016). During non-cropping seasons in the alternate system the kelp and manure fertilisers were added. This mimics some alternate cropping systems where animals may graze the area and input nutrients through the incorporation of their manure into the system, or the planting of cover crops which are left in-situ as a residue soil amendment.

Fertiliser type was found to interact with cropping system to affect crop yields. Kelp and manure-based fertilisers were comparable in their ability to increase yields from continuous to alternate cropping systems. The long-term use of kelp fertiliser has potential negative effects such as the build-up of salinity or elements which have a negative effect on crop growth, however, this was not directly measured or realised in this experiment. Other studies have found thresholds where plant vigour decreased after concentrations of seaweed extract increased (Quastel & Webley, 1947). This was due to increased salinity in the growing environment. However, the growing environment used in this experiment was a closed system, of soil free media, which could account for some differences. It is possible that differences in thresholds could be due to the transport of Na^+ to lower depths of the mesocosm away from the plant roots in this experiment during the watering process. Or the pre-treatment of the kelp fertiliser i.e., an extensive washing process as described in 6.2, was sufficient to remove most of the kelps surface residues of Na^+ along with physical debris that may contaminate the experimental set up. It was likely that this process had been sufficient to remove salt residues present at concentrations which would have been detrimental to plant growth, however the level of salt in the growing media once kelp had been added as a fertiliser treatment was not quantified. It should be noted that it is coastal agricultural systems where the use of kelp would be most common due to proximity and these coastal agricultural lands will already experience higher levels of salinity from windblow (Viaud et al., 2023). Some grassland plant communities are more salt tolerant giving rise to halophytic communities such as Atlantic salt meadows (Gennai et al., 2022). The need for the development of salt-tolerant arable crops has become increasingly important in the face of rising salinity levels in agricultural soils worldwide (Sultan et al., 2023). As a consequence of factors such as irrigation practices, climate change, and poor water management, soil salinity poses a severe threat to yields (Eswar et al., 2021). The development of salt-tolerant arable crops is crucial to sustain agricultural productivity in regions affected by salinity, ensuring food security for growing populations (Sultan et al., 2023). Crop varieties have been developed with enhanced salt tolerance, by employing selective breeding, advanced genetic and biotechnological approaches. By identifying and incorporating genes associated with salt tolerance, these efforts aim to create resilient crops capable of thriving in more saline environments (Rasheed et al., 2022). Whilst it is recognised that these salt resistant crop varieties are primarily developed for arid environments (Sultan et al., 2023), there is potential that salt resistant temperate crops could also be developed and utilised in coastal marginal soils such as in the Lazybed system alongside side the application of kelp fertilisers potentially leading to improvements in yield (Corwin, 2021; FAO and ITPS, 2015).

Nitrate levels in the kelp-fertilised mesocosm were slightly lower than in the manure and kelp+manure fertiliser mesocosms, however, this did not have a detrimental effect on yields. This supports the findings from previous work (Chapter 3) and adds further weight to the hypothesis that kelp-induced changes in yields are due to the presence of plant growth hormones in addition to changes in the nutrient status of the soils.

When evaluating the research outcomes from this chapter, the limitations of the methodological approach must also be considered. Although efforts were made to control the climatic conditions in the glasshouse, this was not realised. Temperature and light conditions varied significantly over the four growing periods, with the warmest and brightest conditions found in growing period 1 and 2, with a notable drop in temperature and radiation receipts in growing period 3 and 4. These varying conditions likely account for the inter seasonal yield differences, however treatment differences still persisted and could be assessed. Ideally this experiment would have been conducted over four growing seasons in a field setting on an area of historically cultivated Lazybeds, although this was not possible due to the time constraints of a PhD. Further, the use of a positive control treatment, in the form of artificial fertilisers would have allowed for better comparisons to be made relating to the efficacy and sustainability of the treatments.

Overall, the results presented in Chapter 6, demonstrate that when fresh kelp is used as a fertiliser, the effects on increases in yields, changes to soil properties and long-term sustainability are comparable to manure-fertilised systems. This research provides further evidence, that the use of organic fertilisers is essential in cropping systems, as yields in the unfertilised control mesocosms were dramatically lower, after four growing periods once the growing media nutrient supply had been exhausted. It should be noted that inorganic fertilisers were not tested in this study, given the variety of environmental issues associated with their use in agricultural systems would automatically make it unsustainable. However, further work is needed in real world/field systems, such as Lazybeds, over longer time periods, with many more growing periods to determine whether the use of kelp or manure fertilisers in alternate cropping systems is the most sustainable production method. Moreover, assessments should be made as to whether systems which only produce a crop every other growing period can deliver a more sustainable agroecosystem whilst producing yields sufficient to demand. Further, an assessment of how cover cropping rather than a fallow ley period would affect soils functions in a kelp-fertilised system should be investigated.

7. General Discussion

7.1 Synthesis of Key Research Findings

For millennia, soils in agricultural systems have been modified through the application of organic fertilisers (Bogaard et al., 2013) and the creation of ridge and furrow structures with the aim of increasing productivity in marginal systems (often characterised by low nutrient status and waterlogged conditions in North West Europe) (James Hutton Institute, 2019). One such system is the Lazybed system; where the ridge structures improved drainage and the application of marine macroalgae and manure to the land provided supplementary nutrients (Darling, 1945). The Lazybed system was once commonly practiced in coastal regions in North West Europe particularly Scotland, prior to becoming largely extinct as a result of the Highland Clearances (Dodgshon, 1998) and the rise of modern agricultural practices. However, there is concern over modern agricultural practices that operate at intensive scales to support a growing global population, due to their environmental impact (Gibbs et al., 2015); thus necessitating the need to explore alternative approaches to adapt existing systems and develop more sustainable methods of agricultural production (Brown & Funk, 2008; Jones et al., 2013).

This need was further highlighted by various geopolitical and climate-based challenges disrupting global and domestic food production and supply systems that have occurred over the duration of this research project (Mehrabi et al., 2022). The Lazybed system and its management components offer potential learnings, from which aspects could be adapted and incorporated into modern systems. The overarching aim of this thesis was to better understand whether an abandoned historic agroecosystem, namely Lazybeds, could be re-cultivated and how the use of kelp and dung fertilisers traditionally used in the system affects food production on marginal soil. This was achieved, initially through a review of pertinent literature (Chapter 2) and then via four experimental Chapters (3-6), assessing how the adoption of traditional Lazybed system techniques could enhance agricultural outputs in a sustainable manner, by returning abandoned marginal land to production. To achieve this four research objectives were devised:-

(1) Determine whether Lazybed systems affect soil properties and could support food production on marginal land; (Chapter 3)

(2) Quantify potato production in Lazybed systems; (Chapter 3)

(3) Assess how earthworm communities interact with the differing fertiliser types used in Lazybed systems and whether the presence of earthworms impacts the effectiveness of the fertiliser types; (Chapter 5).

(4) Determine how the use of kelp as a fertiliser treatment differs from more conventionally used fertiliser i.e., manure, to affect food production on marginal land (Chapter 3, Chapter 4, Chapter 6).

This chapter consolidates the findings of the previous four experimental chapters, discussing the implications of their findings from a broader perspective. A general synthesis is given for the experiments in relation to the four aforementioned research objectives and existing literature on this topic and related topics, in addition to a discussion of the key findings, remaining knowledge gaps and recommended future research directions. This research primarily considered the effects on UK coastal marginal agricultural systems, due to their proximity to the natural resources of kelp (Kopittke et al., 2019).

For the first time, this thesis has shown how additions of fresh kelp to soil can produce yields similar to or above those of more traditional soil amendments such as horse- or cattle-derived composted/well-rotted manure in small scale marginal agricultural systems and in controlled laboratory settings using low nutrient soils/growing media. This is likely due to multiple benefits to soil properties such as changes in macro and micro-nutrient content and increases in pH, for which this thesis provides direct evidence, in addition to the hypothesised direct effects on plants such as the presence of plant growth hormones from the addition of kelp, although, this was not measured as it was beyond the scope of this thesis due to technical resource availability. Fresh kelp was repeatedly found to be superior to kelp at various stages in the decomposition process. This mechanism was demonstrated across scales from laboratory to field environments. Direct comparisons to inorganic fertilisers used in the agricultural industry such as ammonium-nitrate were not made through this research. However, the body of knowledge pertaining to the use of inorganic fertilisers is well developed with robust evidence showing how their application in intensive agricultural systems supports crop productivity which has led to advancements in food security and supported growing global populations (Gaffney et al., 2019). If inorganic fertilisers had been used in experimentation, it would have been expected that the results would have shown significant increases in crop productivity above that of the no fertiliser control and above or equal to the effect of adding manure/dung or kelp fertilisers (if application rates are controlled by N content and crop production is limited by N) (Sanderson, 1987). However, it is anticipated that potential synergies may exist in systems that utilise kelp alongside inorganic fertilisers to meet exacting crop nutrient requirements while benefiting from the properties of the kelp. This offers a potential avenue for future research directions that explore integrating learnings from the Lazybed system, into upscaled intensive systems to meet the challenges of climate change and biodiversity loss, while feeding a growing population (Ericksen et al., 2009). Although this research does not propose that the Lazybed system in itself can be upscaled to address the aforementioned challenges.

7.1.1 Lazybed Systems Affect Soil Properties and Could Support Food Production on Marginal Land

Changes in agricultural land management can alter the physico-chemical and biological properties of the soil (Gregory et al., 2009; Powlson et al, 2011). In Chapter 3, it was demonstrated that land re-cultivated under the Lazybed system undergoes changes in soil properties, which can improve marginal land to support crop production. Preliminary studies found differences in soil penetrometer readings between the ridges and furrows, indicating changes in soil compaction and thus infiltration, with the ridges less compact. Chemically, fresh kelp additions mitigated the fall in pH which is often seen over time as a result of the application of animal manure/dung and cropping (Fernandez & Hoeft, 2009). Further the kelp provided a source of macro and micro-nutrients to support crop growth on marginal soils (which are characterised as low in nutrients) (James Hutton Institute, 2019). These changes in physico chemical properties are of a magnitude known to induce changes in soil biology (van Groenigen, 2015), although this was not directly measured in Lazybed systems within the scope of this thesis. A review of the literature considered alongside the results from Chapter 5 indicates that the Lazybed system would likely support or enhance the functionality of existing soil organisms, such as earthworms (Butt et al., 2020; van Groenigen et al., 2014). However, as further discussed in Section 7.1.2, there are multiple interactions between applied kelp and the field ecosystem, which can be both positive and negative. These changes in key soil properties are known to be of sufficient magnitude to induce changes in crop productivity and enhance soil functions (van Groenigen et al., 2014).

7.1.2 Quantification of Crop Production in Lazybed Systems

The findings from Experiments 3.1 and 3.2 offer significant contributions to our understanding of potato production within Lazybed systems, particularly concerning the efficacy of kelp-based fertilisers. Experiment 3.1 elucidated notable differences in potato yields resulting from the application of kelp and dung fertilisers, with fresh kelp demonstrating a distinct advantage in enhancing tuber production above that of the other fertiliser treatments. This observation aligns with previous studies that highlighted the positive effects of seaweed-derived fertilisers on crop growth and productivity (Ali et al., 2021; Knox et al., 2015). Experiment 3.2 further investigated the impact of various kelp-based fertilisers on potato yields and soil properties. Fresh kelp emerged as the most effective fertiliser for enhancing potato yields, followed by combinations of fresh kelp with manure. Experiments 3.1 and 3.2 revealed synergistic effects between kelp and other organic fertilisers, such as dung and manure, on soil properties and potato yields above those of the no fertiliser control. This finding suggests that the simultaneous application of these fertilisers can enhance nutrient availability and promote crop growth synergistically and is partially supported by existing research into the co-benefits of incorporating biostimulants in conventional intensive cropping systems (Sani & Yong, 2022). Experiment 3.2 did not demonstrate a significant increase in potato yields with commercially available seaweed extract, indicating its limited efficacy compared to fresh kelp or kelp+manure combinations at the supplied application rate. Consideration should be given to the application method of the seaweed extract which was applied in one dose and likely diluted through an initial watering and subsequent watering and rainfall. The watering could have rapidly mobilised the fertiliser, transporting it away from plant roots, resulting in limited uptake and plant growth. These results emphasise the need for careful selection and treatment of fertilisers to maximise their benefits in agricultural practices, highlighting avenues for further research into optimising crop productivity and sustainability.

The insights provided by Experiments 3.1 and 3.2 contribute to advancing understanding of the effects of kelp-based fertilisers on potato yields and soil properties. By considering a range of factors such as fertiliser type, processing methods, and synergistic interactions, practitioners can make informed decisions to enhance crop productivity in Lazybed systems and similar agricultural contexts.

7.1.3 The Presence of Earthworms Impacts the Effectiveness of the Fertiliser Types Used in Lazybed Systems

Experiments 5.1 and 5.2 sought to disentangle the complex interactions between earthworms, marine macroalgae (specifically kelp), and soil properties, with respect to crop growth. These findings contribute to our growing understanding of earthworm ecology, the potential use of marine macroalgae as a fertiliser and how earthworm communities respond to it as a food source and impact the efficacy of kelp as a fertiliser in agricultural systems (Butt et al., 2020; Knox et al., 2015).

First, the experiments in Chapter 5 suggest that marine macroalgae, such as kelp, can act as a source of energy and nutrients for earthworms, which supports their growth and reproductive cycles. Despite the lack of direct evidence, the increase in earthworm mass when fed kelp compared to those without access to kelp, implies that earthworms derive some nutritional benefit from kelp consumption.

However, the precise mechanisms behind this phenomenon remain unclear, warranting further investigation into whether earthworms directly consume kelp or benefit indirectly from the byproducts of kelp digestion by soil microorganisms.

Secondly, the experiments highlight the nutritional differences between marine macroalgae and traditional earthworm food sources like horse manure and birch leaves. Marine macroalgae, such as kelp, contain higher levels of salt and phenols, and have a higher C:N ratio compared to terrestrial sources (Butt et al., 2020). These differences in nutritional composition may influence earthworm growth and health, with higher salt levels potentially disrupting osmotic balance, increased phenols affecting digestibility, and elevated C:N ratios leading to slower decomposition processes.

Moreover, the experiments reveal more on the role of earthworms and microbial communities in nutrient cycling and crop growth in kelp-amended soil. While earthworms can enhance nutrient release from kelp and mobilise plant growth hormones, the effectiveness of these mechanisms may vary depending on factors such as earthworm communities (species composition and abundance) and kelp degradation level. The experiments also suggest that earthworms could potentially result in a small increase in the carbon content of the substrate, further influencing soil properties and crop growth, which aligns with existing literature into the effect of earthworms on soil carbon in temperate European soils (Thomas et al., 2020).

Experiments 5.1 and 5.2 demonstrate the complex relationship between earthworms, marine macroalgae and soil properties in supporting crop growth. They underscore the need for further research to elucidate the mechanisms behind earthworm-kelp interactions, including the role of microbial activity, and to assess the long-term effects of earthworms and the wider food web on crop growth in kelp-fertilised systems.

7.1.4 How the Use of Kelp as a Fertiliser Treatment Differs from More Conventionally Used Fertiliser i.e., Manure, to Affect Food Production in Marginal Soils

The utilisation of animal and plant manures in traditional agricultural practices has long been acknowledged for replenishing soil nutrients depleted during cropping cycles (Bogaard et al., 2013). However, the comparative effectiveness of marine macro algae, historically used as a soil amendment in Northwestern European coastal communities, remains less understood (Knox et al., 2015). While previous studies have demonstrated the potential of marine macro algae extracts to enhance crop productivity (Ali et al., 2021), this thesis aimed to evaluate how the application of kelp, whether fresh or partially decomposed, can match or surpass the productivity-enhancing effects of conventional soil amendments and commercially available macroalgae extract.

The investigation into the impact of kelp on crop production revealed that anticipated negative effects on crop growth were not realised. This aligns with some prior research findings, although inconsistencies exist, particularly regarding the influence of kelp applications on soil salinity and subsequent crop development. For instance, studies examining the germination of pak choi seeds in kelp waste extracts (from alginate production) revealed nuanced responses, with lower concentrations promoting germination while higher concentrations caused inhibition (Zheng et al., 2016). Similarly, investigations into sandy soils treated with varying levels of marine macro algae indicated a decrease in microbial respiration attributed to salt thresholds reached at the highest marine macro algae application rates (Haslam & Hopkins, 1996). However, the experimental approach used in this thesis involved pre-treating kelp by washing it with clean water, a method historically guided by the practice of leaving middens of kelp to be washed through with rain prior to application to land, a method that resulted in the removal of surface residues of salt and debris that may have otherwise contaminated the experiment. Although, soil salinity in the experiments was not measured, leading to incomplete research in this area.

Comparing kelp with traditional soil amendments such as manure revealed varying effects on soil properties crucial for plant growth, such as nitrate levels. Application of fresh kelp in Lazybed systems resulted in enhanced yields across diverse crops, performing equally to or above that of other fertilisers including dung, decomposed kelp, mixed kelp+dung, commercially available bagged manure, and liquid fertilisers containing seaweed extract. The differential impact of fertiliser type on yields can be attributed to numerous factors including their inherent properties, direct effects on soil, and crop-specific responses.

Although alterations in soil properties like nitrate content, pH, C:N ratio, moisture, and carbon were noted when using fresh kelp and manure/dung, not all soil amendments resulted in comparable increases in yield. This suggests that factors beyond traditional indicators of soil fertility are influencing crop productivity. Existing literature suggests that plant hormones and growth regulators abundant in kelp, though rapidly degrading, may stimulate early plant growth processes (Shukla et al., 2018). Furthermore, studies have indicated that marine macroalgae fertilisers can induce changes in soil microbial populations, enhancing soil function through increased enzyme activity crucial for nutrient cycling.

7.2 Future Research Directions

The research presented in this Thesis, demonstrates the pressing need to develop our understanding of the potential role that historic agroecosystems, namely the Lazybed system, could have in meeting current sustainable food production needs, however, knowledge gaps remain. The research outputs of this thesis were limited by the COVID-19 pandemic, resulting in a loss of field time (two out of three planned growing periods on the Isle of Rum) and a shift in focus to more controlled experiments in the glasshouse and laboratory. Building on the findings and limitations of this thesis the following areas of research are recommended.

i. A laboratory experiment to determine how concentrations of plant growth hormones in kelp are affected by temperature and moisture over time using a hormone degradation assay.

ii. A study to assess how multiple components of the soil food web respond to kelp additions, to further the work presented in this thesis on earthworms. Specifically, microbial and mesofauna effects could be assessed through the sterilisation and defaunation of the soil and kelp additions, followed by the reintroduction of individual soil dwelling species or assemblages.

iii. An assessment of the metabolomic phenotypic plasticity of a variety of crops in response to kelp additions to reveal how primary metabolism or defence mechanisms are bolstered with kelp as a fertiliser, thereby enhancing our understanding of its agronomic potential.

iv. Determination of how the different hormones present in kelp affect crop growth, using hormone degradation assays, under differing conditions including those present in composting processes. Allowing for mechanisms behind the increase in plant growth observed to be disentangled and to discover whether this is controlled by a single hormone, or combined effects present in kelp.

v. An assessment of the sustainability of kelp. To consider how the removal of kelp and other marine macroalgae from coastal ecosystems and their transfer to agroecosystems might affect the natural coastal ecosystem processes.

vi. A practical field study to determine the viability and long-term effects of the Lazybed system in modern coastal communities. This study would also have a social sciences aspect in terms of an assessment of workload and facilitating the adoption of these practices amongst local communities.

vii. An assessment of the area of land historically cultivated under the Lazybed system and how much of that land offers scope for recultivation in part using remote sensing.

7.3 Environmental Impact and the Scalability of Harvesting Kelp for Use as a Fertiliser

It is imperative to consider the environmental impact of seaweed harvesting and collection in coastal systems (Hasselström et al., 2018; Thomas, 2018). The resource of kelp washed ashore is variable and vulnerable to disruption in supply. Winter storms, which are projected to increase in severity and frequency under climate change (Pardowitz, 2015), may initially appear to increase the resource availability, with kelp dislodged and brought ashore at a higher rate. Existing research has found that winter storms can have a serious negative impact on natural kelp beds; more frequent and severe storms can reduce the kelp bed's ability to rejuvenate (Sussex Kelp Recovery Project, 2023). In many places the receding kelp enables marine craft i.e. fishing trawlers enhanced access, which causes disturbance and results in further damage to the kelp beds. Therefore, practitioners wishing to use kelp as a fertiliser should consider the threats to supply.

Strategies to upscale kelp availability for use as fertiliser, without exploiting the natural resource, can involve utilising cultivation mats in shallow waters and rope growing methods. While research has underscored the environmental benefits of marine macroalgae (i.e., kelp) farming (which require few inputs and do not place demands on freshwater during growth) it has also brought to light significant challenges (Thomas et al., 2019). For instance, there are limitations to scaling up marine macroalgae harvesting and collection practices without causing adverse impacts on coastal and marine environments. Marine macroalgae farms can have varied impacts on coastal and marine ecosystems, contingent upon factors such as farm design, location, and management practices (Thomas, 2018). These impacts encompass habitat alteration, nutrient dynamics, biodiversity, water quality, interactions with other forms of aquaculture, sedimentation, biosecurity risks, and ecosystem service provision. While marine macroalgae farming at scale holds potential benefits for sustainable food production and ecosystem health, careful consideration of its environmental impacts is imperative to ensure the long-term well-being and resilience of coastal and marine ecosystems.

Further, consideration should be given to the resource demands on freshwater if fresh kelp were to be added to land. Throughout the experiments presented in this thesis the kelp was pretreated through a thorough washing process, which mimicked the historical pretreatment, where accounts describe middens of kelp washed through with rainwater over winter to remove surface residues of salt and debris that may otherwise contaminate the soil, making it harder to draw firm conclusions. This pretreatment process used a significant amount of freshwater, a resource often overlooked when assessing the environmental impact of agricultural systems (Ingaro et al., 2023). Demands on freshwater resources are increasing and are expected to rise further as rainfall patterns are disrupted under climate change (Carpenter et al., 1992); by encouraging the widespread use of kelp as a fertiliser resource, additional demands on freshwater resources would add an extra facet to be addressed in an environmental impact assessment, should the washing process be deemed necessary outside of experimental settings. However, the pretreatment of kelp, does not require energy as the water is not required to be heated and standard water pressure is sufficient. If kelp were to be collected and transported on a larger scale mechanisation would be required as the hand collection process is inefficient: this would increase the energy requirement of the process if it were to be implemented on a larger scale.

7.4 Socio-Economic Considerations

It is also pertinent to assess this research in light of key demographic data. Many historic Lazybed systems are located in areas classed as sparsely populated areas. These areas are challenged with a shrinking working age population, which has the potential to have serious impacts on traditional land-based industries, which are still an important cornerstone of the employment market in the sparsely populated areas, despite employment in these sectors falling considerably since 1991 (Hopkins & Copus, 2018). Therefore, unless these demographic trends are reversed (which is improbable without policy interventions) it is unlikely that there would a be workforce present in these areas to oversee the recultivation of lazybeds (a labour-intensive practice) at scale. However, this research does offer scope for recultivation at a community scale; especially for isolate communities, potentially working collaboratively, wishing to become more self-sufficient, explore sustainable methods of food production and reignite lost aspects of Scottish Island culture and heritage. Going forward, research outputs could be in the form of Lazybed system recultivation best practice guidance aimed at communities wishing to undertake such projects. Monitoring of those projects, their adoption and outcomes for such communities, would be of value from a social and ecological perspective.

7.5 Concluding Remarks

The work presented in the four experimental chapters has furthered our understanding of the potential role that historic agroecosystems could have in bringing marginal land back into production. The research underscores the potential of marine macroalgae, particularly kelp (*Laminaria digitata*), as an alternative or supplement to traditional organic soil amendments like manure/dung. In small scale food production systems, kelp could support crop growth in marginal soils, where economic constraints and environmental considerations often render the use of inorganic fertilisers less practical. While the use of inorganic fertilisers may enhance crop productivity in such soils, the approach often proves economically unfeasible due to high input costs and diminished potential returns compared to agronomically "better" soils. Therefore, integrating macroalgae-based solutions potentially offers an avenue for enhancing soil fertility and crop yields in small scale resource-constrained agricultural systems, particularly in areas where it is inappropriate to use inorganic fertilisers due to the presence of protected sites such as SSSIs and wildlife-rich habitats. However, it is also important to consider that even if adopted on small scales, kelp is a natural resource, whose availability is not consistent and potentially threatened by climate change and anthropogenic activity. As previously discussed, demographic considerations also need to be taken in to account, as given current population trends in Sparsely Populated Areas it is unlikely that Lazybeds will be recultivated at scale. However, this research offers scope to support the recultivation in small isolate communities wishing to become more self-sufficient in food production and enhance connections with the area's cultural heritage.

Multiple experiments in the laboratory, glasshouse and field have repeatedly demonstrated mechanisms at play, the cause-and-effect relationships and the real-world applications of the Lazybed system and associated techniques. The strength of this multifaceted approach is that it provides a strong foundation of research to support farmers, policymakers and communities as they look beyond traditional approaches to solve the challenges of the agri-environment nexus.

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9. Appendices

9.1 Appendix 1., Pilot Studies Harris 2017, 2018

In March 2018, two Lazybeds were dug over and were planted with two varieties of potato, (1) Arran Pilot and (2) Pink Gypsy. Overall, 50% of the 24 seed potatoes planted sprouted, with Arran Pilot having a much higher sprouting rate than Pink Gypsy, of 83% and 17% respectively (Figure 50).

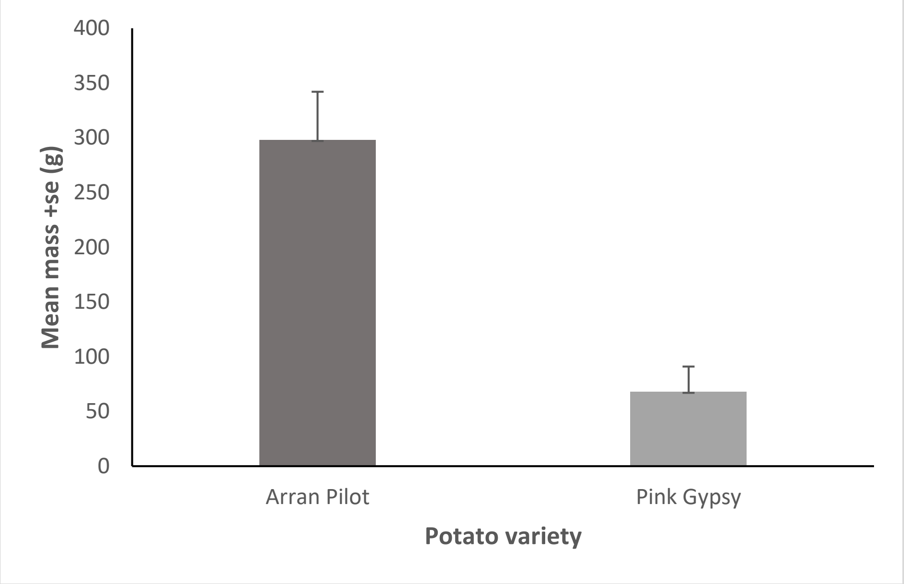

Figure 50 The mean mass of Arran Pilot and Pink Gypsy Potatoes from the 2017 Pilot Study at Harris.

In 2017 and 2018, a further pilot study was conducted at the Harris exclosure, this time to see whether the length of time in cultivation and with that successive applications of fertiliser would affect Arran Pilot yields. Modest increases in yields after two rather than one year of cultivation were observed, suggesting cumulative effects of fertiliser application (Figure 51). Both one- and two-year fertilised plots produced yields far greater than the no fertiliser plots

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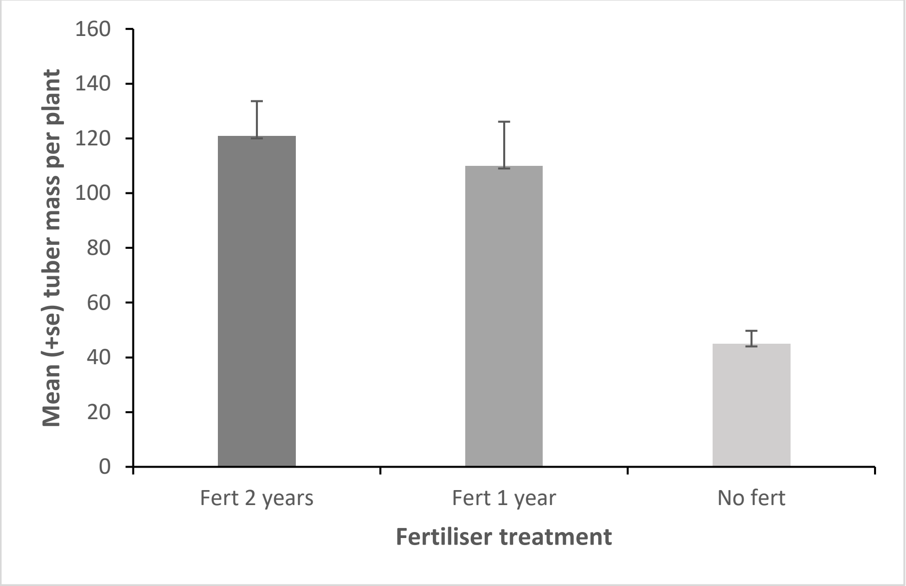

Figure 51 The mass of Arran Pilot potatoes by fertiliser treatment at Harris.

9.2 Appendix 2., Harris, Isle of Rum, Baseline measurements soil properties and vegetation

This experiment was devised to determine baseline values for soil properties on the abandoned Lazybeds at the Harris Research Station and to assess potential effects of the exclosure, prior to experimentation.

Prior to the construction of the exclosure soil depth was recorded to be > 1.2 m (which was the full extent of the corer). Soil penetrometer readings (10 for ridges and 10 for furrows) were taken across the area to be covered by the exclosure, readings for ridges were higher, indicating higher levels of compaction (Table 9).

Table 9 Soil compaction measurements taken from the ridge and furrows, prior to the construction of the exclosure.

Furrows reading	**Ridges reading**
220	210
220	280
360	440
160	410
140	320
180	290
280	300
260	460
270	480
200	580

Two parallel transects were marked out, spanning the exclosure, pilot study recultivated beds and a ~5 m buffer either side of the exclosure. In total 30 points were marked, 15 were ridge locations and 15 furrow locations. Six points were on the pilot study recultivated beds. Soil samples were taken from each of the 30 locations and testes for soil moisture, LOI, pH, nitrate, phosphate, C:N. Further, walkover vegetation surveys along the transects identified the species present at the site (Figure 52).

Figure 52 Surveying the vegetation along a transect inside and outside of the exclosure at the Harris Research Field Site, October 2018

Results

The recently recultivated beds had lower moisture content. The exclosure did not affect moisture content. Moisture in the ridges were LOI, nitrate and phosphate did not differ across the site. LOI values were high (19% C) indicating highly organic soils. pH values were higher in the pilot study recultivated beds, generally higher in ridges, however spatial differences were observed, with values outside of the pilot study recultivated beds between 6.96 and 5.32. Nitrate, ammonium and phosphate readings for the soils were generally low and did not differ between ridges and furrows (Table 10). Vegetation surveys inside and outside the exclosure in July 2019 reveal that these grasslands contain a variety of graminoids, forbs and legumes. The vegetation inside and outside the exclosure was dominated by grasses, commonly *Nardus stricta, Holcus mollus and Festuca ovina*.

Table 10 Soil property data from baseline measurements at Harris

Test	Mean	SD
Ammonium KCl (mg/L)	8.14	6.25

Nitrate KCl (mg/L)	1.9	3.12
Phosphate Olsen P (mg/L)	5.43	1.99

9.3 Appendix 3., Experiment 5.3 An investigation of the effects of earthworm population density and kelp additions on selected soil properties.

Rationale

To find the optimal population density to use for experiments in earthworm- kelp studies. The difference in feed quality between kelp and more conventional well studied food stuffs in likely to differ in its ability to support earthworm populations.

Methods

A fully factorial experiment was set up to test how the population density of earthworms together with additions of kelp affect soil properties (Table 11). In this experiment two levels of kelp treatments were tested: zero; and 40 g of kelp additions. To test the effects of earthworm number, three levels of earthworm density were selected: zero; two; and four individuals per mesocosm. The earthworms were laboratory-grown adult *Aporrectodea calignosa*, kept as detailed (Lowe & Butt, 2005). Each earthworm was washed and had mass determined, prior to experimentation. Efforts were made to ensure an even distribution of earthworm masses across treatments. Earthworm and kelp treatments were applied to the mesocosms, with six treatments combinations in total. Each treatment was replicated 5 times.

Mesocosms were set up by adding 650 ml of moistened Kettering loam (60 % moisture content) to 750 ml pots, with six air holes in the lid created using a mounted needle. At this stage samples of kelp and Kettering loam were sub-sampled to test for moisture and carbon content, CN, pH, nitrate and micronutrient analysis. These sub-samples were first passed through a 2 mm sieve, oven-dried at 105 ^{o}C until a constant mass was reached, then placed in the furnace at 535 ^{o}C for 4 hours to determine moisture and LOI, respectively. The pH was determined by adding 5 g +/- 0.1 g of substrate to a 50 ml corning tube (Conical Sterile Polypropylene Centrifuge Tubes (Thermo Fisher Scientific)), plus 25 ml of DI water, shaken for two hours, then the liquid phase filtered through Whatman no. 1 and measured using a Hanna probe (type).

Mesocosms were then placed in an incubator at 15 ^{o}C in constant darkness. Soil moisture levels were checked at weekly intervals over four weeks. After two and four weeks, 35 g of soil was removed from the top 3 cm of each mesocosm without disturbance to the earthworms and processed and tested for moisture and carbon content, CN, pH, nitrate and micronutrient analysis as detailed above. Particles of kelp accidently removed were returned to the mesocosms.

The experiment terminated after four weeks, the earthworms were removed, washed, blotted dry and had masses determined. Visible particles of kelp were removed by hand, cleaned to remove any residual soil and left to air dry for 7 days until a stable mass was reached.

Table 11 Details of the earthworm and kelp treatments used in this experiment.

Treatment	Earthworm treatment (no. of individuals per mesocosm)	Fertiliser treatment
1	0	No additions
2	2	No additions
3	4	No additions
4	0	Kelp

5	2	Kelp
6	4	Kelp

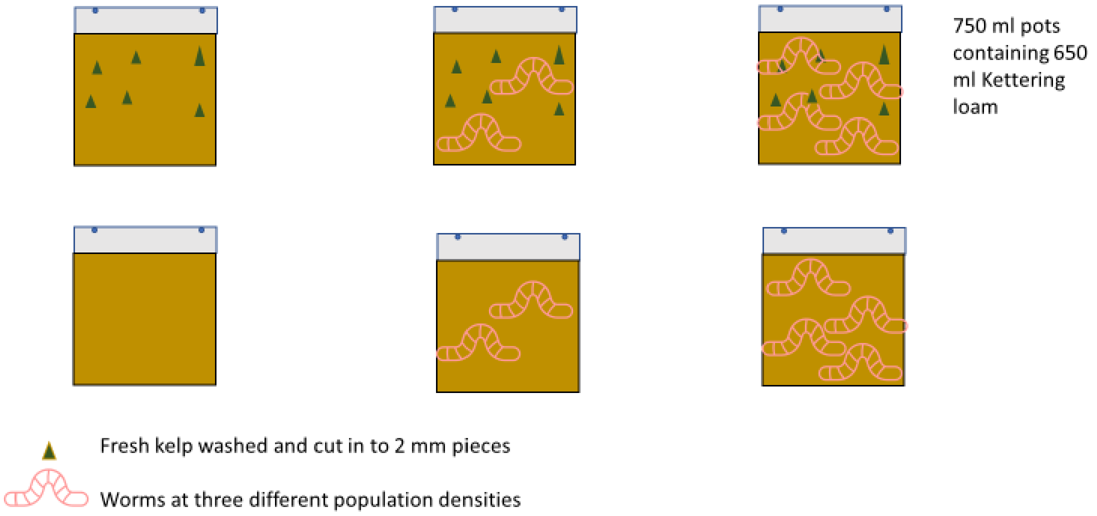

Figure 53 Experimental design for experiment 5.3.

Results

Kelp and earthworm density are significant controls on soil moisture at T1 ($p < 0.01$, $p < 0.05$, respectively) and T2 ($p < 0.001$, $p < 0.001$, respectively). The interaction between kelp and earthworm population density is not significant, however, the p value has dropped markedly from T1 (0.350) to T2 (0.075). It is interesting that the level of significance for the individual treatments increases over time. The change in the significance of the interaction between kelp and earthworm treatments over time, suggests that effects of kelp and earthworm population density are becoming more pronounced over time. It will take time for the kelp to be incorporated into the soil, changing soil properties. The same observations could be made in regard to the significance of the individual treatment effects on soil moisture.

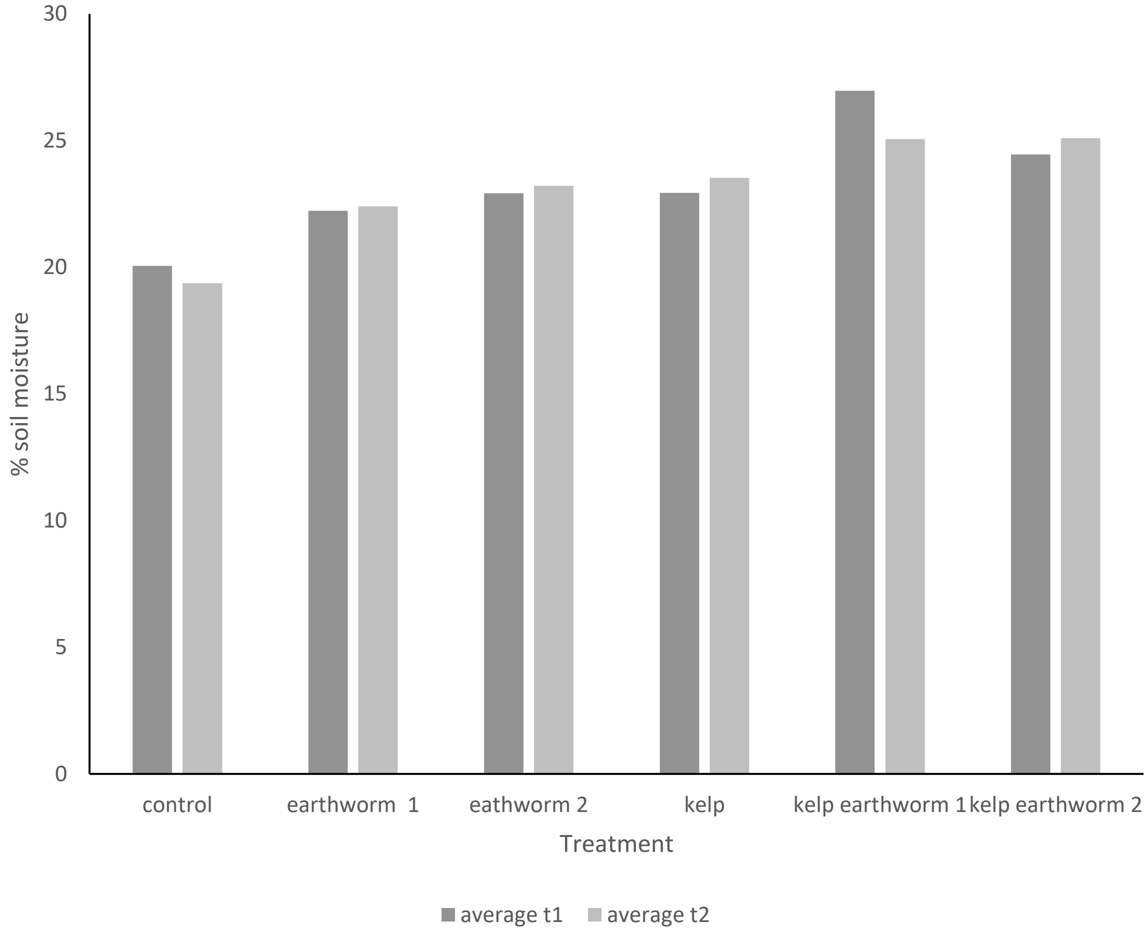

Figure 54 Soil moisture values by treatment in experiment 5.3.

When no kelp is added earthworm mass reduces in the highest earthworm density mesocosm. In the lower earthworm density mesocosms there is a small increase in average earthworm mass. When kelp is present, earthworm mass increases more in the lower density earthworm population, than at the higher earthworm population density. The presence of kelp significantly affects the average earthworm mass increase ($p < 0.0001$). The population density of earthworms also affects the average mass increase of the earthworms, where worms in the lower population densities gained more mass than earthworms at the higher population densities ($p < 0.0001$). The interaction between kelp treatment and earthworm mass change was significant ($p < 0.001$).

9.4 Appendix 4., Experiment 5.4. A comparison of earthworm species fitness when kelp is given as a food source

Rationale

Fresh kelp additions have been found to greatly increase crop (potato) yields in poor nutrient status soil. The role of earthworms in incorporating organic matter fertilisers such as animal manure into the soil is well documented, however, it is unclear whether the same effect will result if the organic matter input is switched to kelp. Earthworm effects on the incorporation of kelp into soil were tested across three earthworm treatments; two different species and a species mix of earthworms.

Aim

How do different species of earthworms utilise kelp as a food source and what are the subsequent effects on soil properties?

Hypotheses

Different earthworm species will utilise the kelp food source at differing rates. This will affect the mass of kelp remaining and the relative mass increase of the earthworms at the end of the experiment.

The differences in kelp feeding by the different earthworm species will affect soil properties such as nutrients availability, carbon content and structure.

Method

The species (*Aporrectodea longa* and *Aporrectodea caliginosa*) selected for this experiment were based off the species which were sourced from the field. The species listed below are a starting off point. The number of replicates can be reduced to four if no further individuals are found in table 12.

Table 12 Earthworm assemblages for the treatments in Experiment 5.4

Earthworm 1	Earthworm 1	Replicates	Treatment ID
Longa	*Longa*	5	L
Longa	*Caliginosa*	5	CL
Caliginosa	*Caliginosa*	5	C

1. 15 x tubs (750 ml) for worms with air holes, containing 650 ml of moistened Kettering loam, with water added to meet desired moisture levels, add earthworms (2 adults, the earthworms had their masses determined and sorted so that each pot contains approximately the same biomass of live earthworms) and kelp (40g of washed and cut up into 2 mm pieces, placed 5 cm below the surface of the mesocosm).

2. Earthworms were left in incubators at 15 °C for 4 weeks, then samples of the soil were taken and sorted to remove any remaining residue of kelp.

3. Soil was then tested for pH, moisture content and LOI and the earthworms were recovered and assessed for increases/decreases in biomass

Results

The species composition of the earthworm community determined the mass change. *A. longa* showed a consistent increase in mass in the 0-4 and 4-8 week periods. *A. caliginosa* initially increased in mass, then lost mass in the second measuring period. The same trend was observed with the species mix. No difference in measured soil properties after was found between the different earthworm assemblages (Table 13).

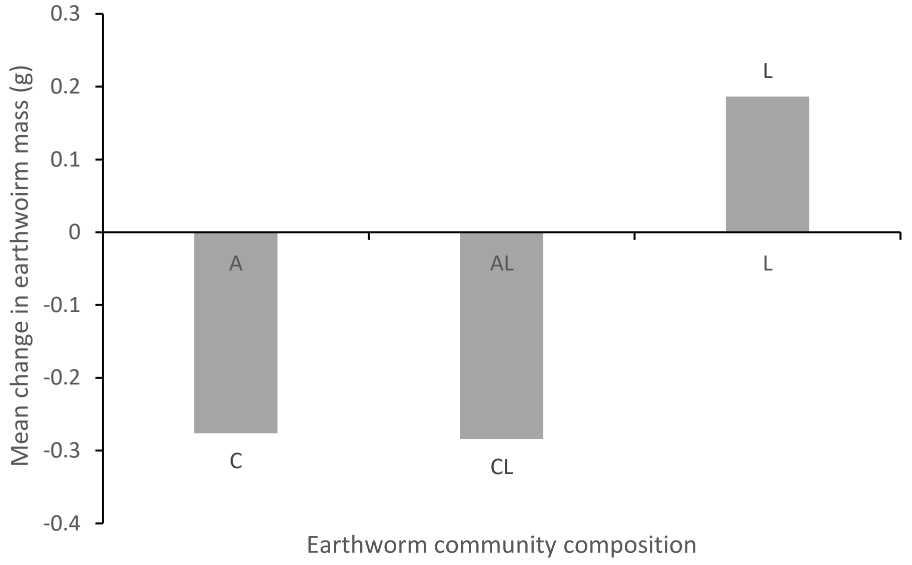

Figure 55 Change in earthworm mass after 8 weeks incubation with only kelp offered as a food source.

Table 13 How soil properties changed in experiment 5.4, after different earthworm assemblages had been feeding on kelp.

Treatment	Mean pH	Mean Moisture	Mean LOI
C	6.87	43.44	4.17
CL	6.81	47.85	4.05
L	6.90	48.13	4.29