An evaluation of the impact of “out-of-season” vegetable production on nitrogen leaching

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Abstract

Nitrogen (N) leaching is a major driver of freshwater degradation in New Zealand. This has resulted in a strong regulatory focus on reducing N leaching rates from intensive land uses in recent years. Of all intensive land uses, vegetable cropping generally has the highest rate of N leaching per land area (Di & Cameron, 2002). Given that the vegetable cropping industry is worth $6.39 billion annually, and the public health necessity of maintaining the supply of fresh vegetables, there is a growing priority to research and develop methods to reduce the N leaching footprint of vegetable production to ensure the future viability of the industry (HortNZ, 2020).

It is often claimed that the need to produce vegetables crops "out-of-season" to satisfy consumer demand for year-round availability of vegetables is one of the reasons that vegetable farms leach such large quantities of N. The validity of this claim has not been explored in a New Zealand context. This thesis aims to fill this research gap by investigating and comparing the annual N leaching rates under "in-season" and "out-of-season" vegetable production, using a case study approach.

The case study is an intensive vegetable cropping block in the Horowhenua, a region renowned for intensive vegetable production. The case study will be focused on two varieties of the *Brassica oleracea L.* species: broccoli and cauliflower. The case study and research question will be investigated using a modelling approach, making use of APSIM and Overseer. A modelling approach was used due to the lack of available field-based data, and the impracticality of collecting field-based data within the time constraints of this thesis. The effect of "out-of-season" production on N leaching was also contrasted with the effect of two good management practices (GMPs): the use of catch crops and minimum tillage. A gross margin analysis was also performed to gauge the financial viability of a seasonal production regime.

Contrary to expectations, the annual N leaching rates (as kg N/ha) under an "out-of-season" production regime were on average 39% lower than the N leaching rates under an "in-season" production regime. This difference was largely driven by higher rates of soil inorganic N through the autumn/winter period (i.e., when most of the annual N leaching occurred) under "in-season" production. The greater quantity of soil inorganic N could be traced to higher quantities of residue N left behind by "in-season" production of broccoli and cauliflower, which was partly explained by higher yields. As such, the key to determining the effect of seasonal production on N leaching is less about the classification of what is "in" season and what is "out" of season, and more about understanding the ability for crops to generate and/or take-up high levels of inorganic N over the autumn/winter period.

While the production of the study crops "out-of-season" led to a reduction in the N leaching rate on a per hectare basis, "out-of-season" production was considerably less efficient in terms of the N leached per unit of yield, leaching 1.6 to 2 times more N per tonne of harvested product than "in-season" production. Hence, while "out-of-season" production of the study crops may reduce N leaching rates per land area, the overall N leaching associated with meeting consumer demand for "out-of-season" vegetables is likely to be much larger than the N leaching associated with meeting the demand for "in-season" vegetables. As such, whether "out-of-season" production is better or worse for N leaching depends on the perspective taken.

The average difference in annual N leaching (as kg N/ha) between the "in-season" and "out-of-season" production regimes were comparable to the reductions achieved through the use of minimum tillage and catch crop GMPs. This supports further research and development of timing-based crop management approaches such as seasonal production in the vegetable cropping industry.

No conclusions were able to be made about the financial viability of either "in-season" or "out-of-season" production from the gross margin analysis.

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1. Introduction

1.1. Background

Clean waterways and a productive primary sector are both important to New Zealand's society and economy. However, productive land use has been detrimental to water quality, with more than 90% of rivers in agricultural catchments having at least one nutrient at above natural concentrations (Ministry for the Environment & StatsNZ, 2020, pp. 36). One major nutrient of concern is nitrogen (N). Excessive N in water is a concern as it can have major ecological consequences, such as excessive periphyton growth and depleted dissolved oxygen concentrations which can impact freshwater invertebrates and fish (NIWA, 2016). It can also have both acute and chronic effects on human health if in elevated concentrations in drinking water (Ward et al., 2018).

While all primary land uses will typically leach some N, some production systems are worse than others. One industry receiving ample attention currently is intensive vegetable cropping. Of all intensive land uses, including dairy farming, it is thought to have the highest rate of N leaching per land area (Di & Cameron, 2002). The industry has high rates of N loss due to high fertiliser inputs, frequent cultivation, relatively short periods of plant growth, a low nutrient use efficiency, and the incorporation of large quantities of crop residue into the soil after harvest which releases mineral N as it decomposes (Di & Cameron, 2002). With increasingly stricter water quality standards and environmentally aware consumers, improving nutrient management practices is essential for the future viability of the $6.39 billion industry (HortNZ, 2020).

There have been many approaches taken to improve the environmental sustainability of the food production. These have been at the governance, producer, and consumer level. Often, approaches at the central and regional government level dominate discussion, and so initiatives adopted by consumers are given less attention. However, as consumer and producer choices have the potential to shape the future of food production, consumer and producer driven initiatives warrant investigation. One popular consumer approach to sustainable eating is to eat seasonally. That is, to eat foods which are "in-season" and to limit consumption of foods which are "out-of-season". Despite the popularity of seasonal eating amongst environmentally conscious consumers, and repeated claims of the detrimental impacts of "out-of-season" production on N leaching at a recent grower conference, differences in N leaching under "in-season" and "out-of-season" production have not been widely researched (ACRE Group Conference, Massey University, 2020). The definition of seasonal production used in this thesis is presented in section 2.6.1.

For the vegetable cropping industry to be viable in years to come, including a social license to continue operating, N leaching rates will need to be dramatically reduced. As such, growers need to know if the "out-of-season" production of crops is exacerbating the problem of N leaching. If such claims about "out-of-season" production are well-founded then a relatively simple mitigation measure presents itself; to desist from growing crops "out-of-season". Although, this is much easier said than done given the expectation from consumers that most vegetables will be available year-round.

This thesis will investigate whether a production regime where vegetables are grown "out-of-season" leaches more N than a production regime where vegetables are grown "in-season". In anticipation that there may be a financial incentive for growing "out-of-season" crops, gross margin analyses will be performed to gauge the financial viability of each of these production regimes.

1.2. Research Aim and Objectives

The aim of this thesis is to investigate whether growing vegetables "out-of-season" has a higher N leaching footprint than growing vegetables "in-season", using broccoli and cauliflower as case study crops. To achieve this aim, the research will be designed to meet the following objectives:

- Generate a range of crop rotation scenarios illustrating "in-season" and "out-of-season" production of the study crops.
- Model the N leaching rates associated with each of these crop rotation scenarios using APSIM and Overseer.
- Determine whether there are any differences in N leaching under "in-season" and "out-of-season" production of the study crops.
- Compare the magnitude of any differences in N leaching under "in-season" and "out-of-season" production of the study crops with the effect of the adoption of good management practices (GMPs) which seek to mitigate N leaching.
- Assess the financial viability of the various crop rotation scenarios.

1.3. Outline

This thesis is divided into 6 chapters. Chapter 1 provides a brief background on the study area, along with the research objectives and outline. Chapter 2 provides a literature review which outlines and critically analyses literature on a range of topics relevant to the research. Chapter 3 describes the methodology used to carry out the research, including a description of the case study, the development of scenarios which depict "in-season" and "out-of-season" production, the steps taken to model N leaching under these scenarios, and the steps taken to conduct financial analyses of the various scenarios. Chapter 4 presents the results. Chapter 5 will discuss the results in the context of relevant literature. Finally, chapter 6 summarises the research findings and presents the final conclusions.

2. Literature Review

2.1 Freshwater Quality in New Zealand

Deteriorating freshwater quality in New Zealand is a major environmental concern. Specifically, the contamination of freshwater resources with nutrients, sediment, and pathogens is a widely acknowledged issue (Ministry for the Environment, 2020). While each of these contaminants has serious impacts, the focus here will be on N as this is the key contaminant that the vegetable cropping industry and regulators are currently focusing on.

2.1.1 Nitrogen Contamination

2.1.1.1 Rivers and Streams

Rivers and streams in New Zealand are degraded. In catchments dominated by urban, pastoral, or exotic forest land cover, more than 90% of rivers are expected to exceed a nutrient DGV (default guideline value, i.e., an estimation of freshwater quality parameters under natural conditions) (Ministry for the Environment & StatsNZ, 2020, pp. 32 & 36). From 2008-2017, national trends in nutrient contamination of rivers and streams varied considerably by nutrient, region, and land use (Ministry for the Environment & StatsNZ, 2020, pp. 37). Hence, there is no single "blanket" trend that can be used to describe the current national trajectory of nutrient contamination in rivers and streams. However, State of the Environment reporting does suggest that in the Horizons region, 80% of river monitoring sites showed improving trends for soluble inorganic nitrogen (SIN) from 2009-2019 (Horizons Regional Council, 2019, pp. 10).

2.1.1.2 Lakes

The quality of lakes in New Zealand is generally poor. In exotic forest, pastoral, and urban catchments, at least 60% of lakes are classified as eutrophic (Ministry for the Environment & StatsNZ, 2020, pp. 39). In native catchments, this reduces to <20%, suggesting that land use is playing a major role in the poor quality of lakes (Ministry for the Environment & StatsNZ, 2020, pp. 39). Due to a lack of data, national and regional trends in lake water quality are unable to be estimated (Ministry for the Environment & StatsNZ, 2020, pp. 39 & Horizons Regional Council, 2019, pp. 11).

2.1.1.3 Groundwater

The quality of groundwater across New Zealand is varied. From 2014-2018, 44% of monitored sites exceeded the DGV for nitrate-N (Ministry for the Environment & StatsNZ, 2020, pp. 39). However, due to a lack of data, conclusions cannot be drawn about the extent of contamination with other forms of N or other nutrients (Ministry for the Environment & StatsNZ, 2020, pp. 39). Much like rivers and streams, the trends of contamination through time are varied. However, from 2014-2018 more sites had improving trends than worsening trends for the three forms of N measured (total N, nitrate-N, and ammoniacal-N) (Ministry for the Environment and StatsNZ, 2020, pp.39).

2.1.2 Drivers of Degradation

There are many drivers of freshwater degradation in New Zealand. The primary sector is typically assigned most of the blame in the literature, as water quality in agricultural catchments is typically worse than in catchments under exotic forest and native land cover (Ministry for the Environment & StatsNZ, 2020, pp. 32). The general population appear to agree with this, with over half of people who believe that freshwater quality is an issue in NZ, identifying agriculture as the main driver of degradation (StatsNZ, 2019). However, water quality in urban and exotic forestry catchments is also worse than under native land cover (Ministry for the Environment and StatsNZ, 2020, pp. 36). Hence, it is important to note that while agriculture is the most widely discussed driver of degradation in the literature, including in this thesis, that there are many other land use activities which also have a detrimental effect on freshwater quality. The intensity of land use also needs to be considered, as Julian et al. (2017) were able to demonstrate the significance of land use intensity, not just land use itself, on several water quality parameters across a range of agricultural land uses.

2.1.3 Impacts

Elevated concentrations of N in freshwater can have a range of impacts. One of these impacts is on human health. The main human health concern with N contamination is toxicity when found in drinking water. Historically, the main concern has been methemoglobinemia, which is most likely to affect infants (World Health Organisation, 2011). However, in recent years, long-term exposure to nitrate-N in drinking water has also been linked to other acute and chronic health complications. A literature review by Ward et al. (2018) found that exposure to nitrate-N in drinking water was linked to colorectal cancer, neural tube defects, and thyroid disease. Interestingly, they found that many of these complications were associated with exposure at lower levels than what regulatory limits allow (Ward et al., 2018). A study of 114 samples of drinking water in Canterbury found that more than half contained nitrate-N at a concentration higher than a 3.87 mg/L ‘safe’ limit established in a recent Danish study, which is lower than the current regulatory limit (Fish & Game, 2020). Hence, N leaching could be posing a significant public health risk.

Elevated N levels in freshwater also have major ecological impacts. One of these is eutrophication. Eutrophication is "*an increase in the nutrients available in a waterbody which can subsequently increase primary productivity*" (NIWA, 2016). This increase in primary productivity can influence many factors which determine freshwater ecosystem health. For example, the excessive plant and algal growth can increase turbidity which can impact the ability for organisms to see (NIWA, 2016). The increased photosynthesis can also cause fluctuations in dissolved oxygen levels (NIWA, 2016). Most significantly, during the night plants consume oxygen rather than produce it, which can make water anoxic and hence impact the ability of aerobic organisms to breathe (NIWA, 2016).

2.1.4 Policy and Management

In New Zealand, freshwater is managed under the National Policy Statement for Freshwater Management (2020). The objective of the policy is "*to ensure that natural and physical resources are managed in a way that prioritises the health and well-being of water bodies and freshwater ecosystems, the health needs of people, and the ability of people and communities to provide for their social, economic, and cultural well-being, now and in the future*" (National Policy Statement for Freshwater Management, 2020). While the policy provides the national guidelines around nutrient limits in freshwater, the way that resource limits are set in regional plans are the responsibility of regional authorities (National Policy Statement for Freshwater Management, 2020). For example, to ensure that freshwater limits are met, regional authorities may set land use controls, input controls (i.e., fertiliser limits), or output controls (i.e., limits on the concentration of contaminants in discharges or limits on the rate of discharge) (National Policy Statement for Freshwater Management, 2020). In the Horowhenua, the relevant regional authority is Horizons Regional Council, and the relevant policy is the Horizons One Plan, which outlines limits for N leaching (Horizons Regional Council, 2018a). Plan Change 2 will increase the current long-term N leaching limit on LUC Class I land from 25 kg N/ha to 43 kg N/ha/year (Horizons Regional Council, 2018b).

2.1.5 Legacy Effects

Measuring the concentration of contaminants in water has been an important feature of tracking the success of regulatory action against freshwater pollution. While this monitoring has provided useful insight into the impact of changing land management practices and strategies, it is important to note the existence of legacy effects. In the context of freshwater contamination, a legacy effect is the presence of contaminants due to past activities, rather than current activities. Morgenstern et al. (2015) discuss the importance of legacy effects. They were able to demonstrate a lag time of 50-100 years in the Lake Rotorua catchment, meaning that the state and trends in freshwater contamination observed in the catchment today, are likely a result of activities that took place 50-100 years ago. Conversely, this means that the impacts of improved land management in this catchment may not be fully observed for this same period in the future. As such, the impact of local lag time and consequent legacy effects should be considered when analysing the current state and trends in freshwater, and conversely, the impact that current land management practices will have in the future.

2.2 Nitrogen

This section will provide background information on N in the context of the relationship between the soil-plant system and freshwater resources.

2.2.1 Role in Plants

N is essential for plant growth (Bernhard, 2010). It is required in large quantities in agricultural plant systems, with most plants typically containing 1-6% N on a dry matter basis (McLaren & Cameron, 1996). Within plants, N is a component of many essential biomolecules such as proteins, chlorophyll, and DNA (Bernhard, 2010). As such, the impacts of N deficiency are detrimental to plant growth, yield, and survival.

2.2.2 Cycle

N takes many forms and undergoes many transformations in the soil-plant system (Figure 2.1). N is often the most limiting essential nutrient to plant growth (Ågren et al., 2012). This is because although plants require N in large quantities, most N exists in gaseous form which is inaccessible to plants (Bernhard, 2010). To be accessible to plants, N must be present as nitrate-N (NO_3^-) or ammonium-N (NH_4^+) in soil (Mengel & Kirkby, 2001). However, as many arable crops have a preference for nitrate-N, ammonium is likely less important as a plant available source of N in the case study (McLaren & Cameron, 1996). Some plants, like legumes, can ‘fix’ N from gaseous N into ammonia-N (NH_3) (Bernhard, 2010). N can also be fixed artificially via the Haber-Bosch process, allowing direct application of N to the soil as fertiliser (Mengel & Kirkby, 2011). Due to the high N demand in modern agricultural systems, the majority of the N utilised in cropping and vegetable systems today comes from synthetic fertiliser (Mengel & Kirkby, 2001). N can also be added to the soil as organic matter. This could be animal waste in grazed systems, or crop residues in cropping systems (McLaren & Cameron, 1996). Once N is present in the soil as ammonia-N, either through leguminous fixation or the addition of fertiliser or organic mater, it can be mineralised into plant available nitrate-N or ammonium-N through a range of biochemical processes (Bernhard, 2010). At this point, the plant is able to access the N.

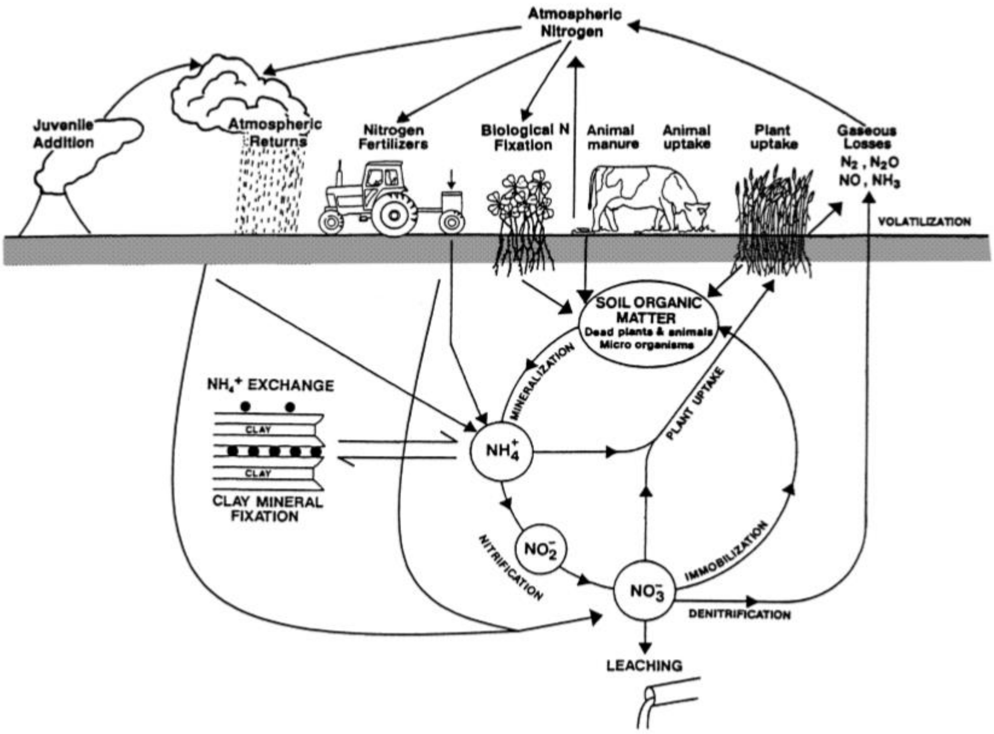

Figure 2.1 Overview of the N cycle. From "Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies", by H.J Di, and K.C. Cameron, 2002, *Nutrient Cycling in Agroecosystems, 46,* p. 238. Copyright 2002 Kluwer Academic Publishers.

While plant available forms of N form only one small portion of the N cycle, they are incredibly important from both a production and freshwater contamination perspective. From a production perspective, they are needed to grow viable crops (Mengel & Kirkby, 2001). From a freshwater contamination perspective, they are important because they are soluble and are hence susceptible to leaching (McLaren & Cameron, 1996). Leaching is most likely to occur when there is both available soil N and adequate soil moisture from rainfall or irrigation to permit drainage. As such, both soil N content and the quantity of irrigation and rainfall are important when considering N leaching. When nitrate-N is leached, it typically enters groundwater, exits the soil as artificial drainage, or enters surface water bodies via lateral flow (Lehmann & Schroth, 2003). In turn, groundwater systems can also be connected to surface water bodies, so nitrate-N initially leached into groundwater can later be transported to lakes and rivers, and vice versa (Lehmann & Schroth, 2003).

2.2.3 Seasonal Variations

This thesis investigates whether producing vegetables "in-season" can help to reduce N leaching rates under intensive vegetable cropping. As such, it is necessary to consider how aspects of the N cycle vary seasonally in such systems. However, much of the research in this area has taken place overseas, particularly eastern Asia. In eastern Asia, the climate and seasons are very different to New Zealand, with most of the annual rainfall associated with the incidence of monsoons (Chang, 2004). Unlike other regions of Asia which typically only experience a summer monsoon, eastern Asia experiences both summer and winter monsoons (Chang, 2004). From a N leaching perspective, this means that there may be drainage, and hence leaching occurring throughout most of the year. In contrast, in New Zealand it is typical to observe most of the annual drainage over a period of 3-4 months over autumn and winter. NIWA reporting of soil moisture parameters supports this, showing that most of the Manawatū-Whanganui region experiences zero days of soil water deficit from late autumn through winter (Chappell, 2015). As such, any seasonal differences in N leaching will likely be related to differences in soil N immediately prior to and during the drainage season in autumn/winter, and seasonal differences in soil N at other times of the year will be less relevant. As such, not all reported seasonal variations in the N cycle will be relevant to this thesis. However, this information will provide important context to the results.

2.2.3.1 Plant Uptake

Studies which have measured seasonal variations in plant uptake of N generally suggest that growth and N accumulation and uptake in plants is highest in spring. In the context of productive crops, this trend has been observed in cucumber, and hydroponic lettuce and tea (Guo et al., 2008, Dijdonou & Leskovar, 2019, Okano & Matsuo, 1996). Each of these studies was able to attribute this spring peak in N uptake to an increase in yield and plant productivity. For example, Dijdonou & Leskovar (2019) found that the dry weight of spring lettuce was 73% higher than autumn lettuce, and 34% higher than winter lettuce. While the autumn lettuce had higher N concentrations that spring lettuce, the spring lettuce still accumulated more N overall due to the considerably higher yield (Dijdonou & Leskovar, 2019). There are obvious limitations to extrapolating these findings to the case study due to the differences in production regime (i.e. hydroponic and greenhouse production vs. outdoor production) and climate. However, these studies do reinforce the fundamental idea that where there is a significant difference in crop yields between growing seasons, that there will also be a significant difference in crop uptake of N.

Several studies have also considered seasonal differences in N uptake in response to variation in N availability. These works illustrate that plants will generally accumulate higher amounts of N when it is seasonally available (Westerveld et al. 2006, Rufat & DeJong, 2001, & Fritschi et al., 2004). While these findings may seem obvious, it is important to discuss them as they confirm the importance of considering not only the physiological behaviour of the plant in controlled environments, but also how that behaviour interacts with differential seasonal supply of N.

Discrete climatic events, such as frosts and floods, can also impact N uptake. Malyshev & Henry (2012) considered the effect of frost on N uptake in grass and found that just one frost event can induce damage which can reduce biomass for an entire growing season. In doing this, a single frost event can reduce N uptake over a similar time period. Although Malyshev & Henry (2012) focused on grass, and not horticultural crops, their findings still warrant consideration in the context of the case study. This is especially true as both air frosts and ground frosts can occur in the lower North Island study area from autumn to spring, although most occur during winter (Chappell, 2014; Chappell, 2015). Floods can also impact N uptake in plants. One reason for this is that floods can reduce crop yield. For example, Singh et al. (1985) were able to demonstrate a 17.7% reduction in the yield of a maize crop following a 24-hour flood. This resulted in the flood-affected crop taking up significantly less N than unaffected crops (Singh et al., 1985). Floods can also induce physiological responses in plants which can impact N uptake. For example, Hsu et al. (1999) were able to demonstrate that in fruit trees, the carbon to N ratio was significantly higher in flood-affected individuals than in unaffected individuals, suggesting that even if yield is not affected by flooding, N uptake still might be. It is important to note that the effects of floods are not restricted to any one season, as there is potential for flooding to occur year-round in the Horowhenua, as even though autumn/winter is the typical wet season, the major 2004 rainfall event (100-year recurrence interval) occurred in February, typically one of the driest months of the year (NIWA, 2018; Chappell, 2015)

Most of the research discussed thus far has looked exclusively at N accumulation in the plant shoots. However, in the vegetable cropping sector where roots and shoots aren’t harvested in equal amounts, it is worth considering whether season has a differential effect on N uptake and content in shoots and in roots, as this could significantly influence the net N removed from soil by a crop. While there has been little work on this topic specifically, He et al. (2010) was able to demonstrate that air temperature had differing effects on N uptake in roots and shoots. Specifically, they found that at a higher temperature treatment (36°C day/30°C night), roots had higher N content than shoots. Conversely, at a lower temperature treatment (28°C day/22°C night), shoots had higher N concentrations than roots. While this is interesting, their temperature treatments are very high compared to the temperatures typically observed in the Horowhenua, even in summer (Chappell, 2015). Hence, it will not be practical to extrapolate this work to the discussion of the case study.

2.2.3.2 Leaching

This section outlines research which has estimated seasonal variations in N leaching from horticultural and arable systems. Of course, given the basic principles of N leaching, there needs to be soil drainage for N leaching to occur. As such, most studies conclude that leaching is highest during the wet season. Given the limited drainage season in New Zealand, this approach is not directly relevant to the case study. However, some authors do highlight interesting points other than drainage which drive seasonal variations in N leaching. The following paragraphs will provide a brief review of some of these points.

Mai et al. (2010) measured N leaching from a range of crops, including types of brassica in Vietnam. They concluded that N leaching was greatest during the wet season. While they could obviously attribute this to the nature of the rainfall and soil drainage in Vietnam, they also noted other processes contributing to the peak during the wet season. Of most significance was mineralisation. They suggest that much of the total annual mineralisation of organic N occurs during the wet season, leading to higher-than-normal stocks of plant available N in the soil, facilitating higher leaching rates. This observation was shared by MacDonald et al. (1997) who were able to demonstrate that most of the N leached in the "high" season (autumn) for N leaching in their case study in England was derived from the mineralisation of N from crop residue. Given that the production of the case study crops in this thesis, particularly broccoli, typically leave high amounts of organic N in the soil as crop residue, seasonal variation in mineralisation, and the potential impacts of this on leaching, will be important to consider in the interpretation of the case study results.

2.3 Nitrogen Leaching in Horticulture

Compared to other intensive industries in the agricultural sector, particularly dairy farming, vegetable cropping is relatively understudied in terms of its role in the decline of freshwater quality. In general, N leaching rates under vegetable cropping are higher than under most other intensive land uses. In most cases, this difference is substantial (e.g., Menneer et al., 2004, Di & Cameron, 2002). For context, Menneer et al. (2004) found that the average reported leaching rate under vegetables was 177 kg N/ha/year, compared to 40 kg N/ha/year and 21 kg N/ha/year in dairy and sheep grazing, respectively. Of course, this work is now somewhat dated, so it is possible that the average values across each of these land uses has decreased with improved nutrient management techniques. However, the considerable disparity in the data does illustrate the enormous potential for N leaching under vegetables crops compared to other land uses.

Di & Cameron (2002) outline some of the factors which make vegetable cropping so susceptible to N leaching. These include high N inputs via fertiliser, frequent cultivation, relatively short periods of plant growth, a low nutrient use efficiency, and the incorporation of large quantities of crop residue into the soil after harvest which releases mineral N as it decomposes (Di & Cameron, 2002). Some of these are inherent and unavoidable. For example, vegetable crops have an inherently low N use efficiency due to their sparse root systems, and hence require higher inputs from fertiliser than other crop types to maintain productivity (Di & Cameron, 2002). However, these factors also suggest that there is scope to decrease leaching rates from the vegetable industry. For example, if crop harvesting can be timed to minimise the amount of mineral N in the soil derived from crop residue when soil moisture is high, this could reduce the impacts of the crop residue on N leaching. However, there is little published evidence of the use of this practice, hence its consideration in this thesis.

2.3.1 Leaching Rates

There have been relatively few attempts to quantify N leaching rates under vegetable cropping compared to other intensive land uses. In addition, only a few of these attempts have been published in scientific journals. A range of methods have been used by those attempting to quantity leaching rates. These include direct measurement of drainage and soil water chemistry, and modelling. Due to the heavy labour and time requirements associated with the direct measurement method, modelling is more commonly used. Some of the models that have been used are Overseer, APSIM, and soil plant atmosphere system model (SPASMO). More information about Overseer and APSIM is provided in section 2.5, as they will be the models used in this thesis. Table 2.1 summarises some of the estimations of leaching rates under vegetable cropping in New Zealand. Information about the methods employed to generate these estimates, and well as the crops modelled, is also included.

Table 2.1 Summary of estimations of N leaching rates under vegetable cropping

Author	Year	Approach	Region	Crops	Leaching Rate (kg N/ha)*
Francis et al.	2003	Measured	Pukekohe	Potatoes	164
				Greens (cauliflower, cabbage and spinach)	134
Williams et al.	2003	Measured	Pukekohe	Spinach	119-292
Norris et al.	2017	Measured	Manawatū	Lettuce, spinach, cabbage	~215**
Crush et al.	1997	Modelled (manual)	Pukekohe	Onions	105
				Cabbage (summer, winter)	16, 20
				Lettuce (summer, winter)	7, 10
				Potatoes (early, main)	217, 31
				Pumpkin	13
Fenemor & Price	2016	Modelled (SPASMO)	Tasman	General vegetables	16-51.4

Thomas et al.	2005	Modelled (Overseer)	Pukekohe	Potato, oats, onion	48**
		Modelled (IPCC)			82*
The AgriBusiness Group	2014a	Modelled (Overseer)	Waikato	Potatoes, onions, carrots, squash, oats	64**
				Broccoli, squash, oats, lettuce, onions, mustard, potato	65**
				Broccoli, mustard, lettuce, cabbage, spinach, cauliflower	73**
The AgriBusiness Group	2014b	Modelled (Overseer)	Horizons (Manawatū-Whanganui)	Potatoes, barley, pasture	15**
				Cabbage, lettuce, spinach, squash, onions, pasture	26**
				Broccoli, spinach, lettuce, cabbage, cauliflower	39**
				Potatoes, carrots, brussel sprouts	17**
The AgriBusiness Group	2019	Modelled (Overseer)	Canterbury	Green vegetables	52**
				Intensive vegetables (no fallow)	43**
				Intensive vegetables (with fallow)	55**
				Root vegetables	39**

Jolly et al.	2020	Modelled (Overseer)	Horowhenua	Cauliflower, broccoli	220
				Cauliflower, potato	134
				Spring onion, spinach, lettuce, maize, cabbage	103
				Maize, spinach, lettuce, spring onion, cabbage	116
Zhao & Legarth	2020	Modelled (APSIM)	Bay of Plenty (Kaituna)	Sweetcorn, broad beans	44
			Bay of Plenty (Rangitaiki)		64.8

* Over the winter drainage season unless specified.

** N leached over a full year. Note that some works which utilised this approach have provided a long-term annual estimate which includes several years under pasture.

2.3.2 Influence of Crop

In horticultural systems, mineral N present in soil is derived from many sources. For example, it may be from unused fertiliser, or it may be derived from the mineralisation of crop residue, as was demonstrated by Mai et al. (2009) and MacDonald et al. (1997). The amount of crop residue varies enormously between crops. High residue crops, like broccoli, generally facilitate higher rates of N loss via leaching than crops with lower amounts of crop residue, like cabbage, even under similar management, due to the ability for N to be mineralised from the residue. LeRoux et al. (2016) illustrate this point well, as they found that the average grey water footprint (and hence N leaching potential, due to their method of grey water footprint calculation) of broccoli was 9.5 times higher than that of cabbage (LeRoux et al., 2016). Hence, it is clear that the type of crop, especially with respect to differing amounts of crop residue, can have a significant impact on N leaching rates.

2.3.3 Contribution of Vegetable Cropping to Freshwater Degradation

There is a lack of work demonstrating the significance of the impact of leaching from vegetable cropping on water quality at a catchment scale. For example, Abell et al. (2011) studied the effect of land use on the water quality of 101 lakes across New Zealand and did not find a significant relationship between vegetable cropping and water quality (Abbell et al., 2011). However, "arable cropland" only covered a miniscule 0.4% of their study area, so it is likely that the impact was unable to be detected, as it simply didn't cover enough of the study area. Another potential reason for the non-detection is that the "arable cropland" category they used combined "arable cultivation" with orchard, vineyard and other perennial crop land uses, which typically have a much lower leaching rates than vegetable cropping (Abbell et al., 2011; Di & Cameron, 2002). Hence, this grouping technique may have hidden some of the impacts of vegetable cropping.

While multi-catchment studies have been unable to draw a link between vegetable cropping and water quality, targeted studies of heavily cropped catchments do suggest a link. Bloomer et al. (2019) studied water quality in the Arawhata catchment in the Horowhenua, where two thirds of the catchment area is used for intensive vegetable cropping. They concluded that the stream has "one of the highest nitrate levels in New Zealand". Hence, different authors appear to draw different conclusions about the significance of vegetable cropping on freshwater degradation, depending on the scale of focus and the approach taken. Nonetheless, there is evidence to suggest that intensive vegetable cropping is a significant driver of freshwater degradation, even if the detectable effect is localised to the areas of production.

2.4 Study crops

This thesis will focus on two study crops: broccoli and cauliflower. Broccoli and cauliflower are both varieties of the common *Brassica oleracea L* species (Reid & Morton, 2019). They are both considered to be in the top ten "key" crops of the New Zealand vegetable growing industry, and hence provide an excellent opportunity to assess the effect of growing season on N leaching (HortNZ, 2017).

There are many agronomic similarities between broccoli and cauliflower, and furthermore between other varieties of the *Brassica oleracea L* species (Reid & Morton, 2019). However, the amount of N removed and left behind by broccoli and cauliflower is substantially different due to differences in the marketable yield, which is influenced by differences in their harvest index. Broccoli crops have a low harvest index, meaning that only a small portion of the plant is typically harvested, leaving large amounts of crop residue in the soil (Reid & Morton, 2019). In contrast, cauliflower crops have a much higher harvest index, meaning that a larger portion of the plant is harvested, leaving much smaller amounts of crop residue in the soil (Reid & Morton, 2019). This is important in the context of nutrient management, as these crop residues typically contain high amounts of phosphorus, potassium, and organic N (Reid & Morton, 2019; McLaren & Cameron, 1996). While these nutrients can be a valuable resource to subsequent crops, they can also present challenges for managing N leaching. This is because the organic N in the residue can be mineralised and subsequently lost from the soil profile (McLaren & Cameron, 1996). Hence, contrasting the leaching rates of broccoli and cauliflower under different seasonal regimes provides a valuable and unique opportunity to study the effect that seasonal production can have on crops with varying amounts of crop residue.

2.5 Nutrient Budgeting

2.5.1 Definition and Purpose

Nutrient budgeting is an important tool in the management of nutrients in farm systems. At the fundamental level, a nutrient budget is defined as "a tool which estimates the nutrient flows in a farming system" (Ravensdown, 2016). However, there are many ways that this can be done. This is reflected in the wide range of nutrient budgeting tools available, and the broad range of approaches that these tools utilise. Two of the most commonly used models are Overseer and APSIM. While APSIM is increasing in popularity in academia and research, Overseer remains the most widely used tool in New Zealand due to its required use by many regulatory authorities (EnviroLink, n.d.). Both models will be used in this thesis. The following sections will provide some background information about both models, as well as their strengths, limitations, and performance.

2.5.2 Overseer

OverseerFM was developed in New Zealand as a nutrient management tool (Overseer Limited, 2019). Overseer Ltd is owned in equal stakes by the Ministry for Primary Industries (MPI), AgResearch, and the Fertiliser Association of New Zealand, and is a not-for-profit company (MPI, 2020). The interests of these organisations are reflected in the four main objectives of the model:

- "*To produce nutrient budgets to identify nutrient flows through a farm system,*
- *Determine fertiliser nutrient maintenance requirements*
- *Tabulate greenhouse gas and energy emissions, and*
- *Produce indices of production and/or environmental impacts*" (Wheeler, 2016).

The Overseer model works by creating a nutrient budget for a specific physical entity (Wheeler, 2016). This physical entity could be a whole farm, a farm block, or a single paddock (Wheeler, 2016). To calculate the nutrient budget at the block scale, which is what will be done in this thesis, Overseer considers basic inputs and outputs of nutrients, as well as internal transfers of these nutrients within the block (Figure 2.2). Overseer uses site-specific data such as soil type and climate to then provide an estimation of any nutrient deficit or surplus (Wheeler, 2016).

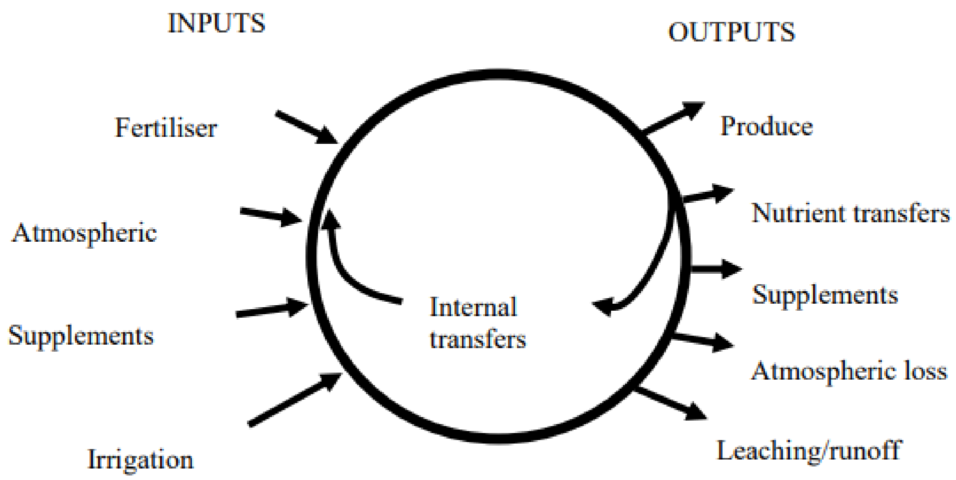

Figure 2.2 Schematic illustration of how Overseer calculates nutrient budgets at the block scale. From "*Overseer® technical manual: Technical manual for the description of the Overseer® nutrient budgets engine*", by D.M Wheeler, 2016. Copyright 2015 OVERSEER Management Services Limited.

The Overseer model has been developed using 30 years of agricultural and environmental research in New Zealand (Overseer, 2020). While developing a model from research ensures that it is evidence based, there have been research gaps which suggest that certain aspects of the model should be approached with caution. In the case of leaching of nutrients from horticultural systems, as noted in previous sections, there has been a lack of research compared to other intensive land uses. As such, the vegetable cropping aspects of the Overseer model are underdeveloped compared to pastoral aspects of the model (Ledgard et al., n.d.). Despite this, the estimation of leaching losses is perhaps one of the most widely utilised aspects of the model given that nutrient leaching has become a major regulatory issue in horticulture, and that the use of Overseer is required by most regional councils. Another key limitation of the cropping model is that it operates at a monthly time step (Ledgard et al., n.d.). This means that any variation at time scales smaller than this will not be captured. This can be an issue in vegetable cropping systems as often multiple fertiliser applications can occur in one month.

A major criticism of Overseer is poor accuracy. One widely cited work claims that Overseer has an uncertainty range of approximately 25-30% when considering farms within the calibration range, and >50% when considering farms outside of the calibration range, which includes vegetable cropping enterprises (Parliamentary Commissioner for the Environment, 2018). Despite the fact that the analysis which provided these uncertainty estimates is not publicly available, they have been widely adopted as a convenient rule of thumb when analysing Overseer outputs (Parliamentary Commissioner for the Environment, 2018).

In response to criticisms about the accuracy of Overseer, Ledgard et al. (n.d.) compared measured field values of nutrient losses with the estimated values provided by Overseer. Given the focus of this thesis, only their analysis of N losses will be considered. The authors considered three different land uses, dairy farming, apple orcharding, and wheat cropping. For the dairy farming and apple orcharding land uses, there was an approximately 9% discrepancy between the measured N loss and the Overseer estimate. For the wheat cropping land use, this discrepancy jumped dramatically to 37.5%. This reaffirms that the accuracy of the model decreases dramatically for arable cropping land uses, which are generally outside of the calibration range of the model. However, the discrepancies measured here are lower than the 25-30% and >50% discrepancy estimates suggested in the previous paragraph.

Despite the widespread criticism of the Overseer model, and the discrepancies outlined here, Williams et al. (2013) conclude that Overseer is still “the best tool currently available for estimating nitrate leaching loses from the root zone across the diversity and complexity of farming systems in New Zealand”. Given that it is still the most widely used tool by regulatory authorities as well, these conclusions are well supported.

2.5.3 APSIM

APSIM is a modular modelling framework that is frequently used to evaluate losses of N via leaching (Keating et al., 2003). The available modules are diverse, and include a wide range of crops, soil processes, and management practices (Keating et al., 2003). The model is developed and maintained by an initiative comprised of various scientific research and government agencies across Australia, New Zealand, and the United States (APSIM, 2021). As such, the model has had significantly more international input than the Overseer model. While this does mean that the research gaps associated with the Overseer cropping model are more likely to be addressed, it does increase the likelihood of research that isn't representative of New Zealand production systems being incorporated into the model.

The user interface of APSIM is considerably different to Overseer. To produce a simulation with APSIM, users utilise both modules and manager scripts. Modules are built by developers, and subsequently "plugged-in" by users (Holzworth et al., 2014). The exact modules used depend on the system being simulated. Manager scripts are defined by the user and can adapt the model and modules to reflect the system being simulated (Holzworth et al., 2014). The modules and manager scripts used in this thesis are outlined Chapter 3.

Aside from the immediately obvious differences between Overseer and APSIM, there are several differences relating to the model processing of scenarios which are directly relevant to this thesis. One key difference is that APSIM simulations operate on a daily time-step, unlike Overseer which operates on a monthly time-step (Khaembah & Brown, 2016). This means that finer-scale temporal variations in soil water, soil N, and plant behaviour, and their effect on N leaching are accounted for (Khaembah & Brown, 2016). In the context of commercial vegetable cropping, this is important as these factors can vary enormously within a single month due to intensive management.

Like Overseer, APSIM has a relatively good track record of estimating N leaching losses from pastoral farming regimes. However, APSIM has a better track record of estimating N leaching from arable and vegetable cropping land uses than Overseer. Khaembah & Brown (2016) compared APSIM estimates of N leaching with measured N leaching data under a crop rotation schedule comprised of vegetable and arable crops and found that there was a strong correlation (R^2=0.88) between measured leaching rates APSIM estimated leaching rates. This is considerably more accurate than the 50% rule of thumb variation in leaching estimates from Overseer (Parliamentary Commissioner for the Environment, 2018). However, other authors have found that APSIM tends to overestimate N leaching rates under an intensive cropping regime (Sharp et al., 2011). As such, while APSIM appears to provide more accurate estimates of leaching than

Overseer, it is still not a perfect model. However, including APSIM will improve the robustness of the results of this thesis, as it will test the seasonal effect of vegetable production under a different interpretation of soil water and N dynamics.

2.5.4 Comparison of N and Soil Water Dynamics in Overseer and APSIM

Overseer and APSIM models are often not in agreement when estimating N leaching losses. In general, APSIM tends to generate higher estimates of N leaching losses than Overseer (Khaembah & Brown, 2016). To interpret and understand any differences in leaching estimations between Overseer and APSIM, it is necessary to consider differences in the ways that the two models model soil N and soil water dynamics. Khaembah & Brown (2016) conducted a thorough review on this topic, so this section will draw heavily on their work.

In terms of the N balance, Overseer tends to make greater estimates of non-leaching losses of N from the soil profile, such as plant uptake and denitrification, which in part, explains the higher estimates of leaching losses from APSIM (Khaembah & Brown, 2016). It is unclear why the estimates of denitrification vary between the models (Khaembah & Brown, 2016). The higher rates of crop N uptake in Overseer are explained by differences in crop yields. That is, in Overseer, the model assumes that the user-defined crop yields are always achieved, whereas APSIM estimates crop yield based on a range of factors, including soil N and climate, meaning that if any deficiency or unfavourable growth conditions are perceived by the model, then crop yield and hence crop uptake of N is limited (Khaembah & Brown, 2016). This issue has not been investigated in depth in the literature but remains a key feature in the development and future use of APSIM.

In terms of the soil water balance, the models are in somewhat better agreement. For drainage, the authors found several instances where the two models generated comparable estimates, although Overseer did have a tendency to provide slightly higher estimates (Khaembah & Brown, 2016). These differences in drainage are not adequately explained by differences in irrigation between the two models, although there were also some discrepancies between those estimates. As such, the discrepancies between the soil water dynamics of the two models are not well understood. Given that estimations of drainage in Overseer are greater than in APSIM, it is unusual that APSIM tends to make greater estimations of leaching than Overseer. This issue has also been recognised by other authors and is explained by an overestimation of nitrate concentrations in soil water in APSIM (Sharp et al., 2011).

2.6 Seasonal Eating

With the ever-increasing demands of feeding the rapidly growing population, there have been a range of alternative diets proposed to reduce the environmental impact of food consumption and production. These range from diets like the "planetary health" diet developed by the EAT Lancet Commission, to other dietary habits popularised in health and environmental media such as eating locally and eating seasonally. While each of these dietary options are worthy of investigation, the focus here will be exclusively on eating seasonally. This section will briefly summarise perspectives on the definition and perceived environmental impacts of seasonal eating, both in popular media and in published material.

2.6.1 Definition

In its simplest form, seasonal eating is eating food that is grown "in-season" (MacDiarmid, 2014). However, with modern international trade of food, the definition of "in-season" food has become complex. For example, if someone in New Zealand eats fruits and vegetables "out-of-season" in New Zealand, but consumes fruits and vegetables that have been grown in-season elsewhere and imported, is this seasonal eating? Or, does somebody need to eat fruits and vegetables in line with the seasons where they live? This has seen the lines blur between eating seasonally and eating locally (MacDiarmid, 2014). For simplicity, this thesis will focus on the production of vegetables for domestic supply only. Given that 91% of most of the key vegetables produced in New Zealand are consumed in New Zealand, this should not impose too many limitations on the findings of this research (HortNZ, 2017). Hence, from this point, the use of the term "in-season" food production is referring to eating seasonal foods from a domestic perspective within New Zealand.

Another issue that arises when defining whether produce is "in-season" or "out-of-season" is that different varieties and improved growing techniques have permitted year-round production for many crops. This means that fruits and vegetables are often available throughout the year. For example, 5-a-day (n.d.) advertising states that vegetables such as broccoli, cabbage, lettuce, and spinach are in "plentiful supply" year-round. However, the yields and availability of these crops can vary significantly between seasons, suggesting that there are still "peak" periods of production (Reid & Morton, 2019; HortNZ, 2017). Despite this, the terms "in-season" and "out-of-season" are not terms frequently used by the vegetable cropping industry, so there is no widely used definition of what seasonal production actually is in the context of the production of the study crops (L. Posthuma, personal communication, 2020). However, to assess the research question adequately, it is important to develop a definition of when crops are "in-season", so that the period of "in-season" production for the study crops and the intervening crops included in the crop rotations can be determined. From this point, for simplicity and based on intuition, the season that a crop produces the highest yields will be deemed to be when the crop is "in-season". If the same yield is achieved in different seasons, then the season where this yield is achieved quickest will be deemed to be when the crop is "in-season".

2.6.2 Environmental Impacts

People that promote seasonal diets often quote that the diet is more environmentally sustainable than a diet where produce is consumed "out-of-season". However, there is conflicting scientific evidence about whether this is true (MacDiarmid, 2014). Much of this conflict arises from the broad use of the term sustainability. For example, sustainability could refer to any environmental effect, such as greenhouse gas emissions, resource use efficiency, irrigation water usage, or nutrient losses to the environment. To determine whether eating seasonal produce is more sustainable overall than other dietary choices, a study would need to consider all these impacts. However, due to the complexity of the relationship between diet and such environmental indicators, most studies which have considered the sustainability of eating seasonally have focused only on one of these impacts (MacDiarmid, 2014). These studies have had varied findings. For example, Ayoola et al. (2009) state that the production of vegetables "in-season" is more efficient than the production of vegetables "out-of-season", suggesting that seasonal production may improve resource use and climate change environmental performance indicators. However, Jungbluth et al. (2012) found that while seasonal eating had some benefit for reducing greenhouse gas emissions, it has the lowest relative benefit compared to other dietary changes. Hence, there is not enough literature available to determine whether seasonal eating has a significant, overall environmental benefit. Given this general lack of understanding, and the current heavy focus on N leaching from vegetable crops in New Zealand, the focus of this thesis is aligned to make a valuable contribution to this study area.

2.7 Summary

N contamination of freshwater is a major environmental concern in New Zealand. Despite the general lack of research, it is widely agreed that intensive vegetable cropping generates high volumes of N leaching compared to other intensive land uses. As such, it is necessary to develop methods which can reduce this N leaching. Seasonal eating is framed by some as a way to improve the environmental sustainability of food production. However, its application to improving the environmental sustainability of vegetable cropping with respect to N leaching losses has not been established. Given the scale of the vegetable cropping industry and the increasing urgency around reducing N leaching from the industry, this is a significant research gap. While it is recognised that a wholescale shift to a seasonal production regime would be difficult given the consumer demand for vegetables year-round, this is still a point worthy of further research. The remainder of this thesis will be focused on addressing this research gap.

3. Methodology

3.1 Introduction

This chapter outlines the approach taken to generate and process the data needed to meet the aim and objectives of this thesis. Firstly, the scope of the research is explained. Secondly, the details of the case study are described by outlining the parameters which were entered into Overseer and APSIM. To ensure the fairest possible comparison between the two models, the input parameters into each model were kept as similar as possible. However, the type and format of the information required by each model are often different, meaning that the exact parameters required by each model were also often different. As such, the input parameters will be explained as they were entered into each model. Thirdly, the steps taken to model the case study under minimum tillage and catch crop GMPs are outlined. Lastly, the steps taken to perform the financial analysis are explained.

3.2 Scope

Using a case study approach, this research aims to investigate the effects of the timing of crop rotations on the annual amount of N leached. The case study focuses on two crops: broccoli and cauliflower. The results will be interpreted in the context of when these two crops, as well as other intervening crops built into the crop rotation schedule, are "in-season" and "out-of-season".

The case study will be analysed using nutrient budgeting software, Overseer (version 6.3.5), and APSIM. Overseer is the standard model used in the primary sector and by regulatory bodies in New Zealand. Given this, it was important to use Overseer if the results of this thesis are to be relevant to the current debate about the effect of management practices on N leaching. As Overseer simulates leaching under average climate conditions (i.e., as based on 30-years of climate data), it estimates trends in N leaching and the effect of management approaches in an average year. However, it is also useful to estimate trends in N leaching and the effect of management approaches under atypical conditions. As this is beyond the scope of Overseer, APSIM was also used, as climate data can be inputted for any particular year. Hence. the purpose of using both Overseer and APSIM was to be able to contrast how "in-season" and "out-of-season" production influenced trends in N leaching in a) an average year (i.e., Overseer) and b) an atypical year (i.e., APSIM). However, as there are other key differences between the two models (see section 2.5), there will be factors other than climate which contribute to differences in the outputs generated by the two models. Hence, while the purpose of using two models was to gain a more robust understanding of the effect of "in-season" and "out-of-season" on N leaching, based on modelling under different climate conditions and under different interpretations of soil water and N dynamics, it is acknowledged that it will not be possible to attribute the estimated all differences between the two models to the difference in year alone. However, analysing these other factors is beyond the scope of this thesis.

As this is a simulation study, there is no field data being collected to validate the findings. As such, the results and discussion will need to bear this approach and its limitations in mind. Furthermore, the intention is not that either of the models will provide accurate estimations of absolute leaching rates. Instead, it is hoped that the model outputs will inform relative differences in N leaching losses between "in-season" and "out-of-season" vegetable production. In doing this, it is hoped that the processes involved in driving any observed differences can be inferred.

3.3 Case Study

The case study is an intensive cropping block in the Horowhenua region. The Horowhenua region is frequently referred to as "the food basket of the lower North Island" and is considered to be one of the three major vegetable production hubs in New Zealand (HortNZ, 2017). The intensive production in the region is permitted by largely flat topography, fertile soils, and ideal climate. However, there is mounting concerns amongst the community and local iwi about the effect of the industry on water quality in the area, threatening the social license for vegetable cropping enterprises to operate (e.g., Thomas, 2020). Hence, the Horowhenua region provides an excellent case study for reducing rates of N leaching and will be the region of focus in this thesis.

The case study location was used to source soil types and characteristics, and climate information. The management practices used were not specific to this block, as the owner had no input or involvement with this project. Instead, crop management practices were derived from a combination of the typical practices in the region, and from industry recommendations of good management practices. The typical management practices in the region were informed by liaising with Luke Posthuma of Page Bloomer Associates who works directly with growers in the area. Industry recommendations of good crop management practices were taken from Reid & Morton (2019). The following sections will outline the details of the case study in the context of parameters entered into both Overseer and APSIM. The source of information for each parameter will also be given in each relevant section.

3.3.1 Location and Climate

The case study block is situated in the Horowhenua between Levin and Ōhau, in an area where commercial vegetable cropping is prevalent. As the owner of this block had no involvement with this project, the exact location of the block will not be disclosed. While the same location was used in both the Overseer and APSIM simulations, the exact climate parameters used by the models varied. This is because the Overseer model utilises long-term average climate data based on location, whereas the APSIM model utilised actual climate data. In APSIM, the MicroClimate module was used, with site data from CliFlo for the period 01/10/2019-01/10/2020 (NIWA, n.d.). The 2019/2020 year was chosen as rainfall patterns over the autumn/winter period were atypical compared to an average year (Appendix A). This allows the comparison of the soil water and N dynamics under "in-season" and "out-of-season" production to be contrasted between an average year and an atypical year.

3.3.2 Soil

The soil at the study block belonged to the Waitohu series. Palmer & Wilde (1990) classified the Waitohu soil series as an intergrade between a yellow-grey earth and a yellow-brown earth in the New Zealand genetic soil classification system, equivalent to a Brown soil in the current New Zealand Soil Classification (Hewitt, 2010). In Overseer, soil information would normally be added using S-map. However, the Waitohu series at the study block has not been mapped in the S-map database, and so soil parameters were manually entered in Overseer based on an interpretation of Palmer and Wilde (1990). The Overseer input parameters are outlined in Table 3.1. In APSIM, site-specific soil characteristics were borrowed from another ongoing project on the same block, as APSIM requires considerably more complex and detailed soil data than Overseer (F. Avendano, personal communication, 2021). In terms of modules, the SoilWater and SoilArbitrator modules were used.

Table 3.1 Waitohu soil series parameters in Overseer

Parameters	
Soil Order	Brown
Soil Group	Sedimentary
Drainage Class	Moderately well drained
Topsoil Texture	Silt loam
Stoniness	None
Soil Texture Group	Medium

3.3.3 Drainage

Given that the Waitohu soil series is moderately well drained, it is assumed that no artificial drainage is installed at the study block. As such, no information relating to artificial drainage was inputted into either APSIM or Overseer.

3.3.4 Crops

Crop rotation scenarios for the two study crops, broccoli and cauliflower, were built to test the impact of "out-of-season" production on N leaching. The following sections will outline the steps taken to build these scenarios.

3.3.4.1 Scenario Descriptions

A range of scenarios were built for both broccoli and cauliflower to meet the research objectives. That is, scenarios were built with the intention of comparing the N leaching rates under "in-season" production of the study crops with "out-of-season" production of the study crops. Originally, it was hoped that the leaching rates under both "in-season" and "out-of-season" production could be compared with leaching rates under "mixed" or "year-round" production where crops were grown both "in-season" and "out-of-season". However, as Overseer only permits input of two years of crop data, and only calculates N leaching rates for one year, it was not possible to do this accurately. As such, there were two seasonal treatments applied to the study crops: "in-season", and "out-of-season".

In intensive vegetable cropping systems, crop rotation is standard practice (L. Posthuma, personal communication, 2020). To ensure that the scenarios were representative of typical management, it was necessary to include "intervening" crops between rotations of the study crops. Two different intervening crops were used, cabbage and lettuce. The reason these crops were chosen is because they each have different rates of N uptake. Specifically, cabbage has a relatively high N uptake, and lettuce has a relatively low N uptake (Reid & Morton, 2019). This means that the effect of the seasonal treatments can be observed under two quite different natured intervening crops.

In total, there were four scenarios generated in total for each of the broccoli and cauliflower study crops. This reflects the different combinations of the two seasonal treatments and the two intervening crops. These scenarios are outlined and described in Table 3.2 and Table 3.3 for broccoli and cauliflower, respectively.

Table 3.2 Descriptions of each of the broccoli scenarios. The first letter of the scenario name is the study crop (B= broccoli). The second letter denotes the seasonal treatment applied (I= "in-season", O= "out-of-season"). The third letter denotes the nature of the intervening crop grown between rotations of the study crop (H= crop with relatively high N uptake (i.e., cabbage), L= crop with relatively low N uptake (i.e., lettuce)).

Scenario	Description
B-I-H	"In-season" production of broccoli and cabbage (intervening crop with high N uptake)
B-I-L	"In-season" production of broccoli and lettuce (intervening crop with low N uptake)
B-O-H	"Out-of-season" production of broccoli and cabbage (intervening crop with high N uptake)
B-O-L	"Out-of-season" production of broccoli and lettuce (intervening crop with low N uptake)

Table 3.3 Descriptions of each of the cauliflower scenarios. The first letter of the scenario name is the study crop (C= cauliflower). The second letter denotes the seasonal treatment applied (I= "in-season", O= "out-of-season"). The third letter denotes the nature of the intervening crop grown between rotations of the study crop (H= crop with relatively high N uptake (i.e., cabbage), L= crop with relatively low N uptake (i.e., lettuce)).

Scenario	Description
C-I-H	"In-season" production of cauliflower and cabbage (intervening crop with high N uptake)
C-I-L	"In-season" production of cauliflower and lettuce (intervening crop with low N uptake)
C-O-H	"Out-of-season" production of cauliflower and cabbage (intervening crop with high N uptake)
C-O-L	"Out-of-season" production of cauliflower and lettuce (intervening crop with low N uptake)

3.3.4.2 Growing Season

To ensure that the timing of the inclusion of each of the study and intervening crops in the crop rotation schedules reflected the descriptions given in Table 3.2 and Table 3.3, it was necessary to determine when each of the study and intervening crops are "in-season". Table 3.4 outlines this information, based on the definition of when a crop is "in-season" outlined in section 2.6.1, and the Overseer yields outlined in section 3.3.4.4.

Table 3.4 "In-season" production periods for each of the study and intervening crops.

Crop	Season
Broccoli	Winter
Cabbage	Summer
Cauliflower	Winter
Lettuce	Summer

3.3.4.3 Rotation Schedules

Crop rotation schedules were built to reflect the descriptions of each scenario, as outlined in Table 3.2 and Table 3.3. The schedules were built on a two-year template. Across all scenarios, there were two rotations of the study crops (i.e., broccoli or cauliflower) and two rotations of the intervening crops (i.e., cabbage or lettuce). In scenarios depicting "in-season" production, both the study crop and the intervening crop were timed to reflect their "in-season" production period, as outlined in Table 3.4. In scenarios depicting "out-of-season" production, both the study crop and the intervening crop were timed to reflect their "out-of-season" production period, again as outlined in Table 3.4. To ensure that these rotation schedules were consistent with typical local practices, they were built with the assistance of Luke Posthuma of Page Bloomer and Associates. The schedules are presented in Table 3.5 and Table 3.6 for broccoli and cauliflower, respectively.

Table 3.5 Crop rotation schedules of each of the broccoli scenarios

Time		Scenario			
Month	**Year**	**B-I-H**	**B-I-L**	**B-O-H**	**B-O-L**
Oct	1	Cabbage			
Nov	1				
Dec	1		Lettuce	Broccoli	Broccoli
Jan	1				
Feb	1				
Mar	1				
Apr	1	Broccoli	Broccoli		
May	1			Cabbage	
Jun	1				Lettuce
Jul	1				
Aug	1				
Sep	1				
Oct	2	Cabbage			
Nov	2				
Dec	2		Lettuce	Broccoli	Broccoli
Jan	2				
Feb	2				
Mar	2				
Apr	2	Broccoli	Broccoli		
May	2			Cabbage	
Jun	2				Lettuce
Jul	2				
Aug	2				
Sep	2				

Note: The shading around each crop depicts the total time in the ground. That is, the first month of shading is when the crop was planted, and the final month of shading is when the crop was harvested.

Table 3.6 Crop rotation schedules of each of the cauliflower scenarios

Time		Scenario			
Month	**Year**	**C-I-H**	**C-I-L**	**C-O-H**	**C-O-L**
Oct	1	Cabbage			
Nov	1				
Dec	1		Lettuce	Cauli	Cauli
Jan	1				
Feb	1				
Mar	1				
Apr	1	Cauli	Cauli		
May	1			Cabbage	
Jun	1				Lettuce
Jul	1				
Aug	1				
Sep	1				
Oct	2	Cabbage			
Nov	2				
Dec	2		Lettuce	Cauli	Cauli
Jan	2				
Feb	2				
Mar	2				
Apr	2	Cauli	Cauli		
May	2			Cabbage	
Jun	2				Lettuce
Jul	2				
Aug	2				
Sep	2				

Note: The shading around each crop depicts the total time in the ground. That is, the first month of shading is when the crop was planted, and the final month of shading is when the crop was harvested.

3.3.4.4 Crop Yields

The crop yields varied between the two models (Table 3.7). In Overseer, crop yields were able to be entered manually. The yields entered for each of the crops were the default yields suggested by Overseer, as these are reflective of typical yields used by other users. However, in the case of summer cauliflower, this yield did not appear to be representative of a typical crop in the case study production system. In this case, the yield from Reid & Morton (2019) was used. In APSIM, crop yields are predicted by the model, based on a range of soil nutrition and climate factors. The SCRUM crop module was used. In general, the yields estimated by APSIM were generally lower than the yields used in Overseer, especially for winter production broccoli, cabbage, and cauliflower, and both summer and winter production of lettuce (Table 3.7). APSIM generated crop yields were also generally lower than those in Reid & Morton (2019). This is a known issue with the model, as Khaembah & Brown (2016) also raised concern about the accuracy of APSIM generated crop yields. This issue discouraged the modelling of multiple different "atypical" years in APSIM. It will be important to bear this issue in mind when interpreting the results.

Table 3.7 Crop yields in APSIM and Overseer.

Crop	Overseer	APSIM*
	Harvested Yield (t/ha)	
Broccoli (summer)	8	10-11
Broccoli (winter)	12	8-9
Cabbage (summer)	50	51-52
Cabbage (winter)	70	17-19
Cauliflower (summer)	22	33-35
Cauliflower (winter)	30	16-18
Lettuce (summer)	50	1
Lettuce (winter)	50	3

*Yields are quoted as a range as the exact yield for each crop varied between scenarios.

3.3.4.5 Other Management Practices

Other general management practices relating to crop management were also defined in each model. Prior to the planting of the first crop each of the scenarios, it is assumed that the ground is fallow. At the planting of each crop, conventional tillage is used. At the harvesting of all crops, residue is retained.

3.3.5 Fertiliser

Fertiliser application rates and timing were determined from the "*Nutrient Management for Vegetable Crops in New Zealand*" guide by Reid & Morton (2019). Luke Posthuma of Page Bloomer provided advice on which fertilisers to use. For all crops, the first application of fertiliser was YaraMila Complex (12-5-15-8) (Ballance, 2019b). Subsequent applications were YaraBela CAN (27-0-0-0) (Ballance, 2019a). All applications of fertiliser were entered as "incorporated" for the first application, and "surface applied" thereafter. Although it is recognised that real-world practices may differ from recommendations made in Reid & Morton (2019), using this guide was perceived to be the best way to ensure that the study was consistent with recommended good practices for crop nutrition. To calculate the fertiliser application rates from Reid & Morton (2019), the following process was followed:

1. The appropriate crop, variety, and growing season was identified.
2. The recommended N application rate was read from each of the relevant tables, assuming a soil test value of 50 kg available N/ha.
3. The Overseer yields in Table 3.7 were compared with those in the guide. The Overseer yields were used rather than the APSIM yields as they were perceived to be more accurate. Where the Overseer yields were different to those in the guide, a ratio was calculated to reflect this difference. For example, if the yield in Table 3.7 was 50 kg N/ha, and the yield in the guide was 25 kg N/ha, then the ratio was 50/25=0.5.
4. The recommended N application rate was adjusted for differences in yield between the guide and in Overseer using the ratio calculated in step 3. This ensured that the crops received an appropriate amount of N per unit yield. The only exception to this step was lettuce. In lettuce, the original N application rate from Reid & Morton (2019) was used, despite the differences between the yield in Table 3.7 and the yield in the guide. These differences likely exist due to different assumptions about the proportion of the crop that is harvestable (L. Posthuma, personal communication, 2020). This is supported by Reid & Morton (2019) as they state that the harvestable yield in lettuce can vary enormously depending on the crop and market requirements. Hence, despite the differences in harvested yield between the crop in the case study and the crop in Reid & Morton (2019), it is likely that the field yield and hence N requirements of the crop are the same. As such, the recommendations for summer and winter lettuce were taken directly from Reid & Morton (2019). The total amount of N applied to each crop as fertiliser based on this step is presented in Table 3.8.
5. The fertiliser application rate was calculated from the adjusted N application rate calculated in step 4.

6. The number of applications the fertiliser would be split over was determined. This was done by considering several factors, including length of the peak growth curve of the crop (inferred from the "Pasture/crops" tab in Overseer), and the "per application" limits provided in the guide. Note, even though fertiliser was split to avoid exceeding recommended limits, as Overseer operates on a monthly time step, this limit will have been perceived to have been exceeded due to multiple applications in a single month. In APSIM this was more manageable as fertiliser applications were able to be split evenly throughout the month. The number of applications of fertiliser for each crop was as follows:
   - Summer broccoli received fertiliser over four applications.
   - Winter broccoli received fertiliser over five applications.
   - Summer cabbage received fertiliser over five applications.
   - Winter cabbage received fertiliser over five applications.
   - Summer cauliflower received fertiliser over four applications.
   - Winter cauliflower received fertiliser over five applications.
   - Summer lettuce received fertiliser over four applications.
   - Winter lettuce received fertiliser over four applications.
7. The timing of fertiliser applications was determined by considering the peak growth curve of the crop in Overseer and the timing recommendations in the nutrient management guides. The timing of fertiliser applications was as follows:
   - Summer brassicas (broccoli, cabbage, and cauliflower) received fertiliser over the first two months of growth.
   - Winter brassicas (broccoli, cabbage, and cauliflower) received fertiliser over the first three months of growth.
   - Summer lettuce received fertiliser over the first (and only) two months of growth.
   - Winter lettuce received fertiliser over the first 3 months of growth.
8. The quantity and proportion of total N applied in each application was determined. This varied between crops and growing seasons. For summer grown vegetable crops, Reid & Morton (2019) suggest that no more than 20 kg N/ha is applied at planting. This increases to 50 kg N/ha at planting for winter grown crops (Reid & Morton, 2019). As the summer limit at planting is relatively low compared to the total fertiliser requirements of these crops, in some cases, a lower proportion of the total N application was applied in the first application than in subsequent applications (Table 3.8). As the winter limit was not so restrictive, equal amounts of N were applied at each fertiliser application on winter crops.

A schedule of all fertiliser applications is included in Appendix B for reference.

Table 3.8: Total amount of N applied to each crop as fertiliser.

Crop	Fertiliser Applied (kg N/ha)
Broccoli (summer)	51
Broccoli (winter)	94
Cabbage (summer)	179
Cabbage (winter)	143
Cauliflower (summer)	135
Cauliflower (winter)	209
Lettuce (summer)	90
Lettuce (winter)	35

3.3.6 Irrigation

The irrigation regime was informed by Luke Posthuma of Page Bloomer Associates. The same irrigation criteria were used in APSIM and Overseer. The irrigation type was a travelling irrigator. Irrigation was triggered by soil moisture sensors; at 60% plant available water (PAW), 10mm of irrigation was applied. The irrigation season was from December to March. However, irrigation was only applied when there was a crop in the ground, and not when the ground was fallow. As such, some scenarios received either irrigation for only part of the irrigation season. It is important to note that while the irrigation criteria entered into APSIM and Overseer were the same, total amounts of irrigation applied will likely vary due to the differences in the climate data, and soil and plant processes between the two models.

3.4 Alternative Management Practices

One of the objectives of this thesis is to contrast any observed difference in N leaching between "in-season" and "out-of-season" vegetable production with differences in N leaching rates achieved through the use of conventional nitrogen GMPs. As such, two GMPs were applied to each scenario and modelled in Overseer. They were not modelled in APSIM. These alternative management practices used were derived from the "*Code of Practice for Nutrient Management*" by HortNZ (2014). The following sections will outline the GMPs considered, and how they were modelled in Overseer.

3.4.1 Minimum Tillage

HortNZ (2014) recommend that soil tillage should be minimised "as much as practicable" as a GMP. Although the code of practice suggests that this GMP is aimed at reducing soil compaction and runoff, it has been demonstrated to reduce the rate of and potential for N leaching (e.g., Fraser et al., 2010; Mitchell et al., 2009; Foundation for Arable Research, 2008). Hence, the investigation of the impact of a reduced tillage regime on N leaching here is warranted.

The original crop management practices utilised conventional tillage, which is defined by Overseer (n.d.) as "*the inversion of soil with a plough or similar machinery*". To model the reduced tillage GMP in Overseer, the cultivation method was changed to minimum tillage, which Overseer (n.d.) defines as "*a tillage method which does not turn the soil over"*. It is acknowledged that the use of minimum tillage can be difficult when crop residues are being retained, as is done in the case study, and that conventional cultivation may still need to be used at times for the practice to be "practicable". However, this approach was deemed to be the best way to reflect the recommendation given in the code of practice (HortNZ, 2014).

3.4.2 Catch Crops

HortNZ (2014) recommend that catch crops are incorporated into crop rotations to reduce concentrations of soil inorganic N. To model the use of a catch crop in the case study, the catch crop was grown instead of one of the rotations of the intervening crops (i.e., cabbage or lettuce). As such, the season that the catch crop was included depended on the season that the study crop was grown. For scenarios modelling "in-season" (winter) production of broccoli or cauliflower, the catch crop was grown over the summer. In scenarios modelling "out-of-season" (summer) production of broccoli or cauliflower, the catch crop was grown over the winter. The summer catch crop was maize for silage, and the winter catch crop was forage oats. Each catch crop was grown between the two rotations of the study crop. This ensured that the crop was grown prior to the autumn/winter peak in N leaching in the reporting year, so that its effect on reducing soil N could be observed. As such, the maize catch crop was grown in the summer of the reporting year, and the forage oats were grown in the winter of year one. An illustration of the timing of the catch crops in each of the scenarios is outlined in Table 3.9 and Table 3.10 for the broccoli and cauliflower scenarios, respectively. While it is acknowledged that HortNZ (2014) do not explicitly recommend at least one catch crop rotation every two years as has been included here, this was the simplest way to adopt their recommendation using Overseer.

Table 3.9: Timing of the inclusion of catch crops in each of the broccoli scenarios

Time		Scenario			
Month	Year	B-I-H	B-I-L	B-O-H	B-O-L
Oct	1	Cabbage			
Nov	1				
Dec	1		Lettuce	Broccoli	Broccoli
Jan	1				
Feb	1				
Mar	1				
Apr	1	Broccoli	Broccoli		
May	1			Forage oats	Forage oats
Jun	1				
Jul	1				
Aug	1				
Sep	1				
Oct	2				
Nov	2	Maize	Maize		
Dec	2			Broccoli	Broccoli
Jan	2				
Feb	2				
Mar	2				
Apr	2	Broccoli	Broccoli		
May	2			Cabbage	
Jun	2				Lettuce
Jul	2				
Aug	2				
Sep	2				

Note: The shading around each crop depicts the total time in the ground. That is, the first month of shading is when the crop was planted, and the final month of shading is when the crop was harvested.

Table 3.10: Timing of the inclusion of catch crops in each of the cauliflower scenarios.

Time		Scenario			
Month	**Year**	**C-I-H**	**C-I-L**	**C-O-H**	**C-O-L**
Oct	1	Cabbage			
Nov	1				
Dec	1		Lettuce	Cauli	Cauli
Jan	1				
Feb	1				
Mar	1				
Apr	1	Cauli	Cauli		
May	1			Forage oats	Forage oats
Jun	1				
Jul	1				
Aug	1				
Sep	1				
Oct	2				
Nov	2	Maize	Maize		
Dec	2			Cauli	Cauli
Jan	2				
Feb	2				
Mar	2				
Apr	2	Cauli	Cauli		
May	2			Cabbage	
Jun	2				Lettuce
Jul	2				
Aug	2				
Sep	2				

Note: The shading around each crop depicts the total time in the ground. That is, the first month of shading is when the crop was planted, and the final month of shading is when the crop was harvested.

3.4.2.1 Yields and Management

The yields of the catch crops were informed by industry research and publications. The maize crop yield was assumed to be 18 t DM/ha (Glassey et al., 2009; Tsimba et al., 2020). The forage oats crop yield was assumed to be 8 t DM/ha (Horrocks et al., 2009). Although the main purpose of catch crops is to reduce N in the soil, many growers will still apply some N to maize due to the high N requirements of the crop (L. Posthuma, personal communication, 2020). To ensure adequate nutrition, without compromising the ability of the maize crop to reduce soil N, the equivalent of 35 kg N/ha was applied as YaraMila complex at sowing. This rate is consistent with those recommended for soils coming out of long-term pasture, and hence with high amounts of soil N (Horrocks et al., 2009). No fertiliser was applied to winter oats, as this is common practice when growing as a catch crop (L. Posthuma, personal communication, 2020). At harvest, the crops were harvested via cut and carry and exported, and the residue was retained.

3.5 Gross Margin Analysis

A gross margin analysis was performed for each scenario to investigate the financial viability of producing vegetables "in-season", compared to growing vegetables "out-of-season". The analysis was performed based on Overseer yields and inputs only. The following sections will outline the limitations of the gross margin analysis approach, the sources of information used, and the steps taken to complete the analysis.

3.5.1 Limitations

There are several limitations to the gross margin analysis approach. Firstly, gross margin analyses typically only consider the direct expenses and returns related to growing and selling the crop (Jolly et al., 2020). That is, any indirect overhead costs (i.e., land lease costs, capital investments, insurance, and rates) are not normally considered (Jolly et al., 2020). As such, the gross margin will not be able to determine the absolute financial viability of any of the scenarios. Instead, it is intended only as a means of assessing the relative viability of each scenario. Secondly, the accuracy of the gross margin analysis can only be as accurate as the data being used to calculate it. As financial information relating to vegetable crop expenses and returns is limited, in some cases it was necessary to include data where the accuracy was either unknown or subpar. As such, the final gross margin calculations need to be assumed to have a relatively large margin of error. Finally, the gross margin analysis approach is not meant to be used as an economic analysis. That is, it cannot be used to infer the benefit or cost to society as a whole, as externalities are not accounted for. Hence, it is strictly from the perspective of the operator.

In terms of this gross margin analysis, it is also necessary to outline its limitations in accounting for market dynamics and competition. Competition within the commercial vegetable market is typically strong, with most commercial growers supplying to market most days of the year (L. Posthuma, personal communication, 2020). This is because in the event that they cannot supply a product, but another grower can, then their niche in the market can be lost (L. Posthuma, personal communication, 2020). As such, even if growers make slight losses on some crops at some times of the year, they will often still supply this product. However, these complex microeconomic behaviours and dependencies will not be captured by the gross margin analysis. Instead, this gross margin analysis is intended to provide a high-level overview of the general and relative financial margins associated with "in-season and "out-of-season" production of vegetables, based on generic production costs and returns, assuming the production shift in the study block would not affect the business of the rest of the farm.

3.5.2 Data Sources and Calculations

3.5.2.1 Income

The information used to calculate the income for each vegetable crop was taken from the "Li*ncoln University Financial Budget Manual*" (LUFBM) and consumer price indexes (CPIs) from StatsNZ (Lincoln University 2018; StatsNZ, 2021). Both of these sources provided monthly average prices of crops, so the difference in returns per unit yield between "in-season" and "out-of-season" production was able to be captured. For this analysis, it is assumed that crops are harvested at the end of the month shown in Table 3.5 and Table 3.6 and were sold at the beginning of the following month.

Information from the LUFBM was used preferentially to the CPIs as it provided the prices paid to the growers, whereas the CPIs provided the cost paid by consumers at the final point of sale. However, the LUFBM only contained information for broccoli and cauliflower (Lincoln University, 2018, pp. 77-79). As such, the prices of the other crops in the rotation had to be calculated from the CPI. To estimate the price that the growers would have received from retail prices, the retailer mark-up needs to be removed. However, there is little reliable data available about the typical retail mark-up on fresh vegetables. As such, an average mark-up was calculated by comparing the grower prices from the LUFBM for broccoli and cauliflower in 2018 with the CPIs in the same year. This revealed an average mark-up of 102%, which is roughly consistent with a 2011 survey which found that supermarkets routinely place a 100-300% mark-up on fresh vegetables (Reid, 2011). As such, a 102% mark-up was subtracted from the StatsNZ CPIs to estimate the grower prices for cabbage and lettuce. As the prices for broccoli and cauliflower in the LUFB were for the 2018 year, the prices of cabbage and lettuce were also taken from this year. These prices were all then adjusted for inflation to the fourth quarter of 2020 (Reserve Bank, 2021).

3.5.2.2 Production Costs

The information used to collate production costs for each crop came from a wide range of sources. Table 3.11 outlines the sources of data for each component of the gross margin analysis for each crop, and the steps taken to adjust the values to represent the specific crops in the case study. As the data used to calculate the gross margins was of varying age, it was important to account for this. As such, all values obtained that were published prior to 2021 were adjusted for inflation. This was done by using data from the Reserve Bank of New Zealand (2021) to determine the inflation rate between the date of the published figure and the first quarter of 2021. The original figure was then multiplied by the inflation rate, to estimate the present-day value. Given that this adjustment was made to every variable, where relevant, it is not listed as an adjustment in Table 3.11.

Table 3.11: Sources of information and calculation methods used to estimate production costs

Variable	Source	Adjustment
Cultivation	The AgriBusiness Group (2014b)	N/A
Seed	The AgriBusiness Group (2014b)	N/A
Agrichemicals	The AgriBusiness Group (2014b)	N/A
Fertiliser	Fertiliser- Ballance (2021) Cartage costs- Lincoln University (2018, pp. 171) Application costs- L. Posthuma, personal communication, 2021.	The costs of fertiliser, cartage, and application were multiplied by the amount of fertiliser needed and/or number of applications to provide an amalgamated cost for fertiliser. Cartage costs were based on transporting bagged fertiliser from the Ballance depot in Shannon to south of Levin (~30km).
Irrigation	Foundation for Arable Research (2010).	Irrigation costs were obtained in $/mm/ha. This value was then multiplied by the amount of irrigation predicted by Overseer based on the inputs described in section 3.3.6.
Harvest	The AgriBusiness Group (2014b)	The cost of harvesting each crop was adjusted for differences in yield between the source report and the

		yield used in Overseer (Table 3.7).
Grading	The AgriBusiness Group (2014b)	The cost of grading for each crop was adjusted for differences in yield between the source report and the yield used in Overseer (Table 3.7).
Packing	The AgriBusiness Group (2014b)	The cost of grading for each crop was adjusted for differences in yield between the source report and the yield used in Overseer (Table 3.7).
Freight	The AgriBusiness Group (2014b)	The average cost of freight per tonne across green vegetables in the source report was calculated and was applied to all vegetable crops. This was then multiplied by the yield used in Overseer (Table 3.7).
Commission	The AgriBusiness Group (2014b)	The average cost of commission, as a percentage of sale value, was calculated across all crops in the source report.
Levies	Commodity Levies (Vegetables and Fruit) Order (2019) & Commodity Levies (Fresh Vegetables) Order (2019)	Both the vegetable and fruit levy (paid to HortNZ) and the fresh vegetables levy (paid to VegetablesNZ) were applied to the sale value of each crop.

3.5.2.3 Gross Margin Calculation

A gross margin was calculated for each individual crop in each of its growing seasons. This means two gross margins were calculated for each crop, one to represent its gross margin when grown "in-season" and one to represent its gross margin when grown "out-of-season". This was to ensure that the differences in the costs and income generated by crops at different times of year were taken into account. To calculate the final gross margin for each crop, the costs of production per hectare were simply subtracted from the income generated by that crop per hectare. To calculate the gross margin of each scenario, the gross margins of each of the crops in the reporting year were simply added together. As such, the gross margins will be quoted in $/ha/year.

4. Results

4.1 Leaching Rates

The APSIM and Overseer models generated considerably different estimates of N leaching under both broccoli and cauliflower, with APSIM typically reporting higher leaching rates than Overseer. These differences were expected, based on the inherent differences between the two models discussed in section 2.5. It is not anticipated that the effect of using long-term average climate data (i.e., in Overseer) and 2019/2020 climate data (i.e, APSIM) has driven these differences. Across the broccoli scenarios, Overseer generated estimates ranging from 42-79 kg N/ha, and APSIM generated estimates ranging from 70-140 kg N/ha (Table 4.1). Across the cauliflower scenarios, Overseer generated estimates ranging from 45-89 kg N/ha, and APSIM generated estimates ranging from 84-198 kg N/ha (Table 4.1).

Table 4.1: Estimated leaching rates. Results are reported in kg N/ha for the second year of the schedule outlined in Table 3.5 and 3.6 for broccoli and cauliflower, respectively.

Scenario	APSIM	Overseer
B-O-H	103	42
B-O-L	70	65
B-I-H	122	72
B-I-L	140	79
C-O-H	113	60
C-O-L	84	45
C-I-H	182	89
C-I-L	198	89

4.2 Comparison of Overseer and APSIM Parameters

The APSIM and Overseer models are inherently different from one another. As mentioned, the reason that the two different models were used was to contrast how “in-season” and “out-of-season” production influenced annual leaching rates under a) a “typical” year, and b) in 2019/2020 where there were atypical variations in climate. However, due to other inherent differences between the two models, there will be factors other than climate which contribute to different estimations of trends in N and soil water parameters between the two models (see section 2.5). Hence, even though the purpose of using two models was to compare the effect of seasonal production in two different years, it will not be possible to attribute the estimated differences in N leaching between the two models solely to the differences in “year”, and hence climate, alone. However, analysing these other factors is beyond the scope of this thesis. In the following sections, the differences between the basic soil N and water dynamics between the two models will be disclosed for clarity. However, they will not be discussed in further detail.

4.2.1 Nitrogen Balance

As noted, APSIM generated higher estimates of N leaching than Overseer. There were also differences in the estimations of other soil N and moisture parameters between the two models. In terms of estimations of N dynamics, APSIM generated considerably lower estimates of crop N uptake than Overseer (Table 4.2; Table 4.3) This was expected, given the considerable differences in crop yields between the Overseer and APSIM models (Table 3.7). Yield data from Reid & Morton (2019) are somewhere between those estimated by APSIM and Overseer, suggesting that it is possible that the Overseer crop yields and hence N removals by product are over-estimated, and that the APSIM crop yields and hence N removals by product are under-estimated, most severely in lettuce. These differences in leaching and crop uptake of N have led to considerably different N balances between the two models. In general, the inputs and outputs of N in APSIM were more balanced than the inputs and outputs of N in Overseer (Table 4.2; Table 4.3). Without field-based trials, it is not possible to say which is more or less correct.

Table 4.2: Comparison of the N balances generated by APSIM and Overseer for each of the broccoli scenarios. Results are reported in kg N/ha.

	B-I-H		**B-I-L**		**B-O-H**		**B-O-L**	
	APSIM	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**
Inputs	**273**	**275**	**184**	**186**	**197**	**198**	**89**	**90**
Fertiliser	272	272	183	183	194	194	86	86
Irrigation	1	1	1	1	3	2	3	2
Rainfall	0	2	0	2	0	2	0	2
Outputs	**261**	**315**	**179**	**244**	**198**	**244**	**112**	**109**
Product	139	192	39	111	95	187	42	31
To atmosphere	0	51	0	54	0	15	0	13
Leaching	122	72	140	79	103	42	70	65
Net balance	**12**	**-40**	**5**	**-58**	**-1**	**-46**	**-23**	**-19**

Table 4.3: Comparison of the N balances generated by APSIM and Overseer for each of the cauliflower scenarios. Results are reported in kg N/ha.

	C-I-H		**C-I-L**		**C-O-H**		**C-O-L**	
	APSIM	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**
Inputs	**389**	**391**	**300**	**302**	**281**	**282**	**173**	**174**
Fertiliser	388	388	299	299	278	278	170	170
Irrigation	1	1	1	1	3	2	3	2
Rainfall	0	2	0	2	0	2	0	2
Outputs	**344**	**386**	**261**	**307**	**193**	**310**	**179**	**191**
Product	162	251	63	170	80	225	95	134
To atmosphere	0	46	0	48	0	25	0	12
Leaching	182	89	198	89	113	60	84	45
Net balance	**45**	**5**	**39**	**-5**	**88**	**-28**	**-6**	**-17**

4.2.2 Soil Moisture

APSIM consistently estimated lower annual drainage volumes than Overseer, despite the models assuming similar amounts of annual rainfall and irrigation (Table 4.4). This is unusual, given that a lower drainage volume would generally be expected to facilitate lower rates of N leaching. As such, it is clear that the two models handle N dynamics in relation to soil drainage water very differently. The rainfall data used by the two models also implies that the timing of soil moisture dynamics will be different between the two models (Appendix A). Obviously, it will be important to bear these differences in mind when interpreting the data.

Table 4.4 Comparison of APSIM and Overseer soil moisture parameters. Results are reported in mm/year.

	Drainage		Irrigation		AET		Runoff		Rainfall	
Scenario	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**	**APSIM**	**Overseer**	**APSIM**
B-I-H	569	308	20	38	570	740	0	12	1118	1000
B-I-L	607	299	20	23	532	732	0	10	1118	1000
B-O-H	585	309	60	113	596	749	0	17	1118	1000
B-O-L	591	278	60	113	590	769	0	28	1118	1000
C-I-H	569	340	20	38	570	712	0	8	1118	1000
C-I-L	607	332	20	23	532	697	0	13	1118	1000
C-O-H	585	322	60	113	596	738	0	18	1118	1000
C-O-L	591	295	60	113	590	759	0	28	1118	1000

4.3 Effect of Seasonal Production on Annual Nitrogen Leaching Rates

4.3.1 Broccoli Scenarios

Both APSIM and Overseer estimated higher leaching rates in the "in-season" scenarios than in the "out-of-season" scenarios (Table 4.1). In APSIM, the annual leaching rate in B-O-H was 19 kg N/ha less than in scenario B-I-H, and the annual leaching rate in B-O-L was 70 kg N/ha less than in scenario B-I-L (Table 4.1). In Overseer, the annual leaching rate in scenario B-O-H was 30 kg N/ha less than in scenario B-I-H, and the annual leaching rate in B-O-L was 14 kg N/ha less than in scenario B-I-L (Table 4.1).

While the models were in good agreement about leaching rates being lower in the "out-of-season" scenarios than in the "in-season" scenarios, the relative differences between the leaching rates of "in-season" and "out-of-season" scenarios varied considerably. In scenarios containing cabbage as the intervening crop (-H), APSIM and Overseer estimated a 16% and 42% annual reduction in leaching for "out-of-season" scenarios compared to "in-season" scenarios, respectively (Table 4.5). For scenarios containing lettuce the intervening crop (-L), APSIM and Overseer estimated a 50% and 18% annual reduction in leaching for "out-of-season" scenarios compared to "in-season" scenarios, respectively (Table 4.5). Hence, while both models agreed that "in-season" production generates higher leaching rates than "out-of-season" production, which is the key finding here, they were not in good agreement about the magnitude of the difference. It is not clear whether this is due the different climate data utilised between the two models (i.e., typical vs. atypical) or other factors.

Table 4.5 Average annual reduction (%) in N leaching achieved across the broccoli scenarios by producing crops "out-of-season" compared to "in-season".

Alternative Crop	APSIM	Overseer	Average
Cabbage (-H)	16	42	32
Lettuce (-L)	50	18	

4.3.2 Cauliflower Scenarios

Like in broccoli, both APSIM and Overseer estimated higher leaching rates in the "in-season" scenarios than in the "out-of-season" scenarios (Table 4.1). In APSIM, the annual leaching rate in scenario C-O-H was 69 kg N/ha less than in scenario C-I-H, and the annual leaching rate in C-O-L was 114 kg N/ha less than in scenario C-I-L (Table 4.1). In Overseer, the annual leaching rate in scenario C-O-H was 29 kg N/ha less than in scenario C-I-H, and the annual leaching rate in C-O-L was 44 kg N/ha less than in scenario C-I-L (Table 4.1). Hence, as seen in the broccoli scenarios, both models agreed that the leaching rates under "in-season" production were greater than the leaching rates under "out-of-season" production.

The relative differences between the leaching rates of "in-season" and "out-of-season" scenarios between the two models were more comparable than in broccoli. For scenarios containing cabbage as the intervening crop (-H), APSIM and Overseer estimated a 38% and 33% annual reduction in leaching for "out-of-season" scenarios compared to "in-season" scenarios, respectively (Table 4.6). For scenarios containing lettuce as the intervening crop (-L), APSIM and Overseer estimated a 58% and 49% annual reduction in leaching (Table 4.6). Hence, despite the large differences in the absolute estimates of leaching between the two models, they were in relatively good agreement about both the trend and relative effect of the seasonal treatments on their respective leaching rates.

Table 4.6 Average annual reduction (%) in N leaching achieved across the cauliflower scenarios by producing crops "out-of-season" compared to "in-season".

Alternative Crop	APSIM	Overseer	Average
Cabbage (-H)	38	33	45
Lettuce (-L)	58	49	

4.4 Seasonal Variations in Nitrogen Leaching

Given that the seasonal production of crops is a timing-based management approach, it is necessary to outline how growing the study crops "in-season" and "out-of-season" impacts the timing and magnitude of N leaching throughout the year. Both APSIM and Overseer outputs will be presented here. As noted above, due to its use of long-term (30-year) average climate data, Overseer provides an estimation of the seasonal variations N leaching in a typical year. In contrast, APSIM provides a picture of leaching for the 2019/2020 year, where the rainfall and hence soil drainage and leaching patterns varied from the average year (Appendix A).

As expected, across all scenarios, both models agreed that the majority of annual leaching occurs over the autumn/winter period (i.e., March-August) (Figure 4.1A-D; Figure 4.2A-D). In APSIM, 60-71% of N was leached over autumn and winter, and in Overseer, 42-87% of N was leached over autumn and winter (Table 4.7). Given this, it is clear that understanding what factors and processes (other than drainage) drive higher leaching rates over the autumn and winter period, and how these are affected by "in-season" and "out-of-season" production, will be key in determining why "in-season" production generates higher annual leaching rates than "out-of-season" production.

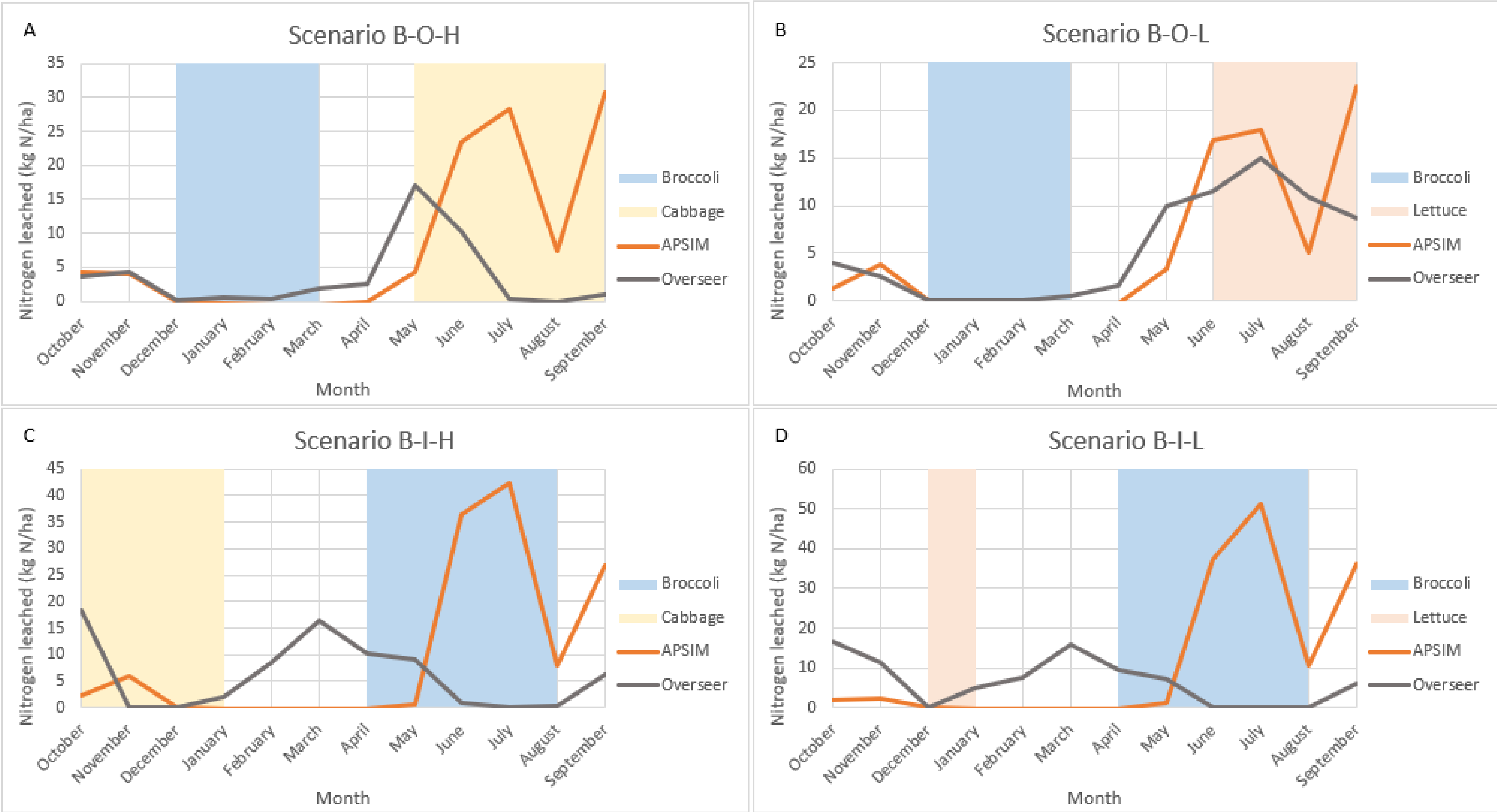

Figure 4.1 Monthly leaching rates across each of the broccoli scenarios in APSIM and Overseer.

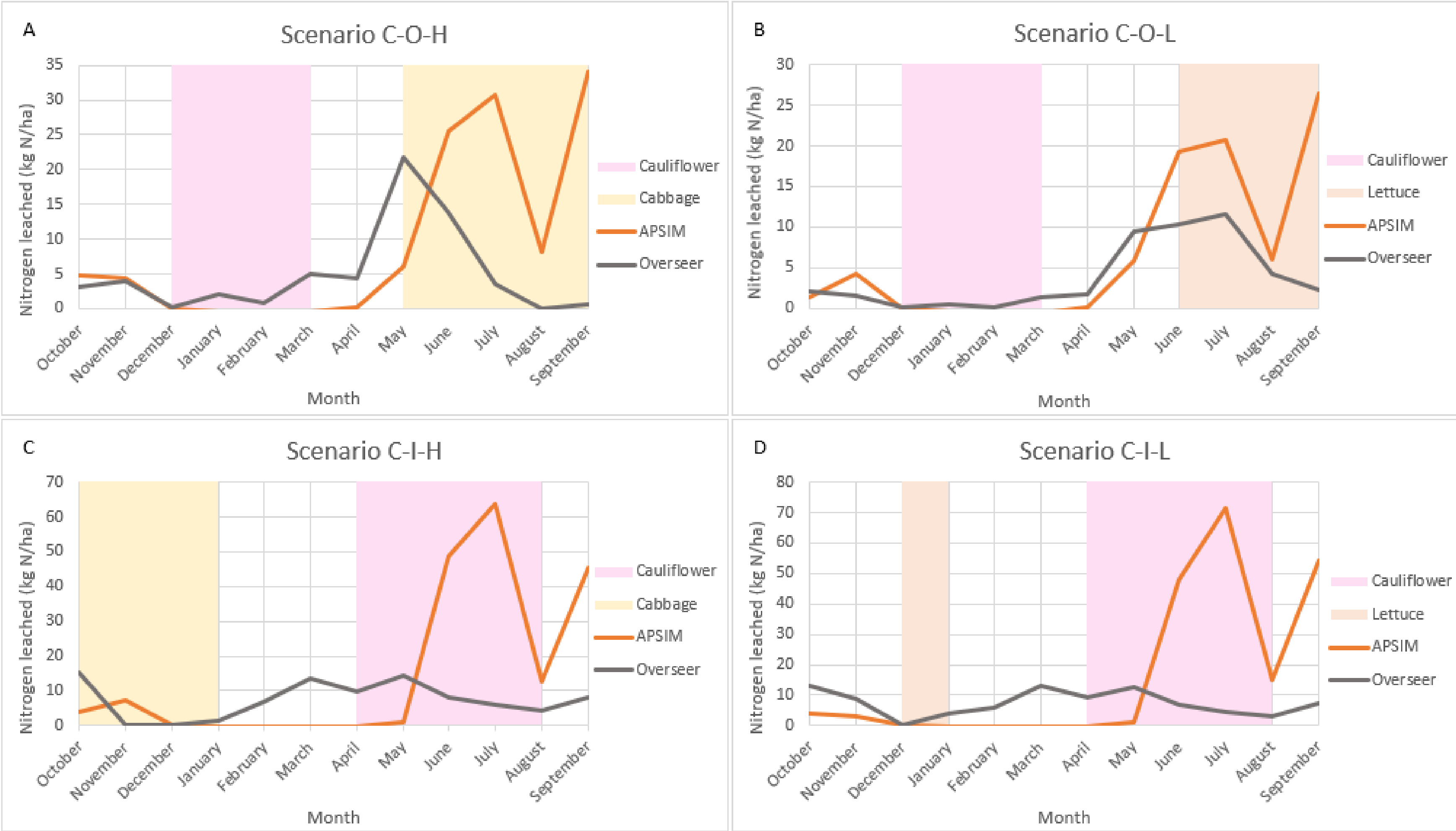

Figure 4.2 Monthly leaching rates across each of the cauliflower scenarios in APSIM and Overseer.

Table 4.7 Total N leached over the autumn and winter period (March-August) across each of the scenarios in APSIM and Overseer, compared to the annual leaching rates.

Scenario	Overseer			APSIM		
	N Leached (kg N/ha)		N leached over autumn/winter (%)	N Leached (kg N/ha)		N leached over autumn and winter (%)
	Autumn and Winter	Annual		Autumn and Winter	Annual	
B-I-H	37	72	51	87	122	71
B-I-L	33	79	42	99	140	71
B-O-H	32	42	76	63	103	61
B-O-L	49	65	75	42	70	60
C-I-H	56	89	63	125	182	69
C-I-L	49	89	55	135	198	68
C-O-H	49	60	82	70	113	62
C-O-L	39	45	87	52	84	62

There were some subtle differences in the timing of N leaching over the autumn/winter period between the two models, and hence between the simulation of an average year (Overseer), and 2019/2020 (APSIM). In Overseer, the onset of the leaching period was earlier than in APSIM. In Overseer, leaching began in autumn, and in APSIM, leaching began in winter (Figure 4.1A-D; Figure 4.2A-D). This is explained by differences in the rainfall distributions between an average year and in 2019/2020 (Appendix A). That is, in 2019/2020, autumn was much drier than in the average year, which contributed to a later onset of autumn/winter drainage and hence leaching in APSIM (Appendix A).

The timing of autumn/winter leaching was more consistent in APSIM than in Overseer. In APSIM, leaching increased sharply in June to reach a maximum leaching rate in July in every scenario (Figure 4.1A-D; Figure 4.2A-D). This is supported by the sudden incidence of rain in June following a dry autumn period in 2019/2020 (Appendix A). In Overseer, the timing of the onset of the autumn/winter leaching period depended on the scenario. In scenarios depicting "in-season" production, the maximum leaching was typically observed between March and May (Figure 4.1A-B; Figure 4.2A-B). In contrast, in scenarios depicting "out-of-season" production, leaching tended to reach its peak rate later in the season, typically from May-July (Figure 4.1C-D; Figure 4.2C-D). As the drainage was similar across all Overseer scenarios, the differences in timing will be related to variability in the timing of the availability of soil inorganic N. This data is presented later in section 4.5.1 and will be a key topic in the discussion of these results.

While the autumn/winter period is clearly important in understanding the differences in annual N leaching between "in-season" and "out-of-season" production, both APSIM and Overseer estimated N leaching in spring, outside of the autumn/winter drainage period (Figure 4.1A-D; Figure 4.2A-D). In APSIM, there was a very sharp peak in N leaching in September across all scenarios (Figure 4.1A-D; Figure 4.2A-D). The timing of this September peak is explained by higher-than-normal rainfall, and hence wetter-than-normal soil conditions in September 2020 (Appendix A). However, as leaching also occurred in September in Overseer, some drainage is obviously typical at this time of year (Figure 4.1A-D; Figure 4.2A-D).

The leaching rate estimated by both models in spring was often comparable to the leaching rates observed over the autumn/winter (Figure 4.1A-D; Figure 4.2A-D). Hence, while the rainfall in September 2020 accounted for in APSIM was abnormally high, it does appear that typical drainage can also lead to significant amounts of N leaching over spring. Hence, even though most of the annual N leaching occurs over autumn/winter, consideration of how seasonal production may influence drivers of N dynamics through to the spring is also warranted.

4.5 Seasonal Variations in Other Nitrogen Processes and Forms

Given that the rainfall data used in each respective model was the same across all scenarios, the differences in N leaching estimated between the "in-season" and "out-of-season" scenarios will be derived from variations in the seasonal patterns of soil inorganic N concentrations. Figure 4.3 supports this statement, showing that the average soil inorganic N concentration over the autumn period (i.e., March-August) accounts for 86% and 98% of the variation in annual leaching in Overseer and APSIM, respectively. Hence, establishing how and why patterns of soil inorganic N vary between the "in-season" and "out-of-season" scenarios will be key to understanding the established relationship between seasonal production and annual N leaching. Seasonal variations in soil inorganic N itself, residue N, the rate of mineralisation of N from crop residue, and plant uptake of N will be presented in the following sections to aid this discussion. Only outputs from Overseer will be presented. This is because the timing and scale of any variations in the various forms of N, and N processes, will likely be more representative of what effect seasonal production will have on N leaching rates in any given year than APSIM, due to the use of long-term (30-year) average climate data, and the use of more sensible yield data (Table 3.7).

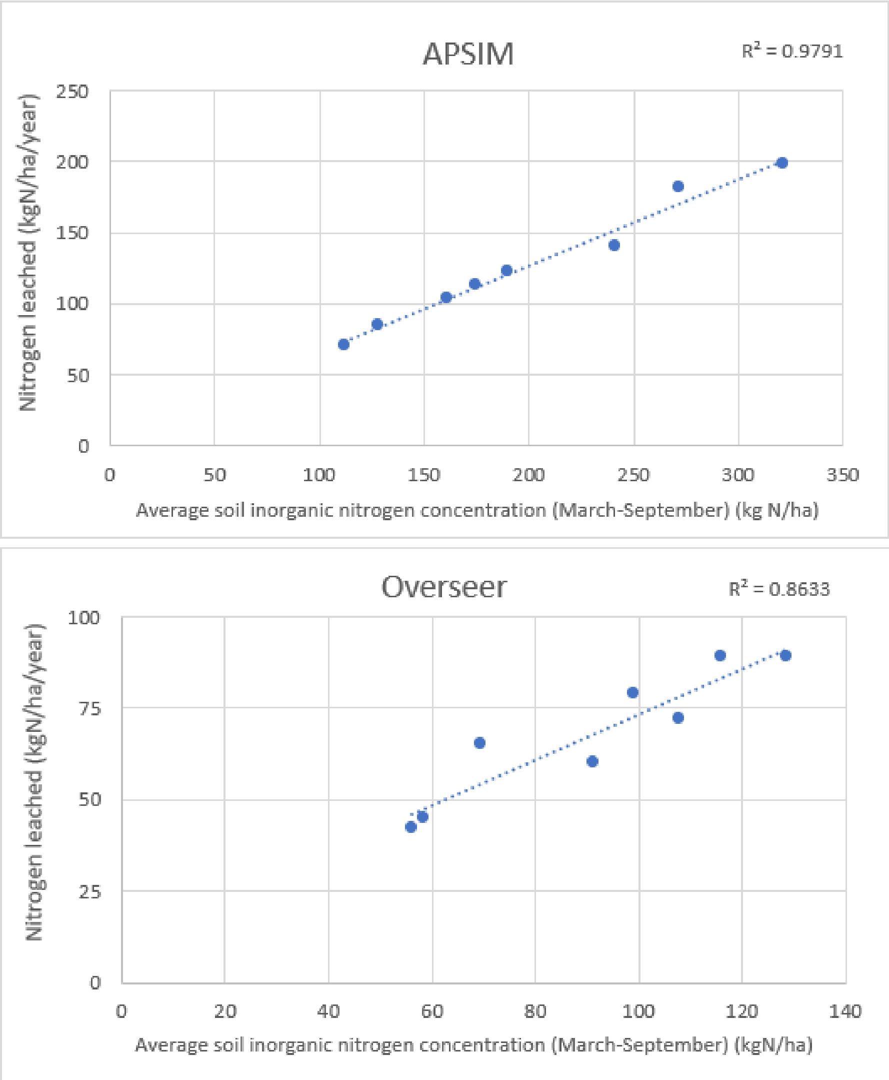

Figure 4.3 Relationship between the average monthly concentration of soil inorganic N over the autumn/winter period and the rate of annual N leaching.

4.5.1 Concentration of Soil Inorganic Nitrogen

Scenarios depicting "in-season" production generated higher inorganic N concentrations than those depicting "out-of-season" production, especially over the critical autumn/winter period (Figure 4.4A-D; Figure 4.5A-D). This was expected given the relationship between rates of N leaching and the concentration of soil inorganic N established in Figure 4.3. The elevated soil inorganic N concentrations over the autumn/winter period in the "in-season" scenarios appear to arise from the study crop grown in the previous year; as the general trend and magnitude of the increase to ~250-300 kg inorganic N/ha in early autumn following the harvest of the "in-season" (winter) broccoli and cauliflower crops in the previous year are starkly similar across all "in-season" scenarios (Figure 4.4A-B; Figure 4.5A-B). The "out-of-season" (summer) broccoli and cauliflower crops also facilitate an increase in soil inorganic N post-harvest; but this is not nearly as large, as soil inorganic N typically peaks at less than half the concentration seen following the harvest of the “in-season” (winter) crops (Figure 4.4A-D; Figure 4.5A-D).

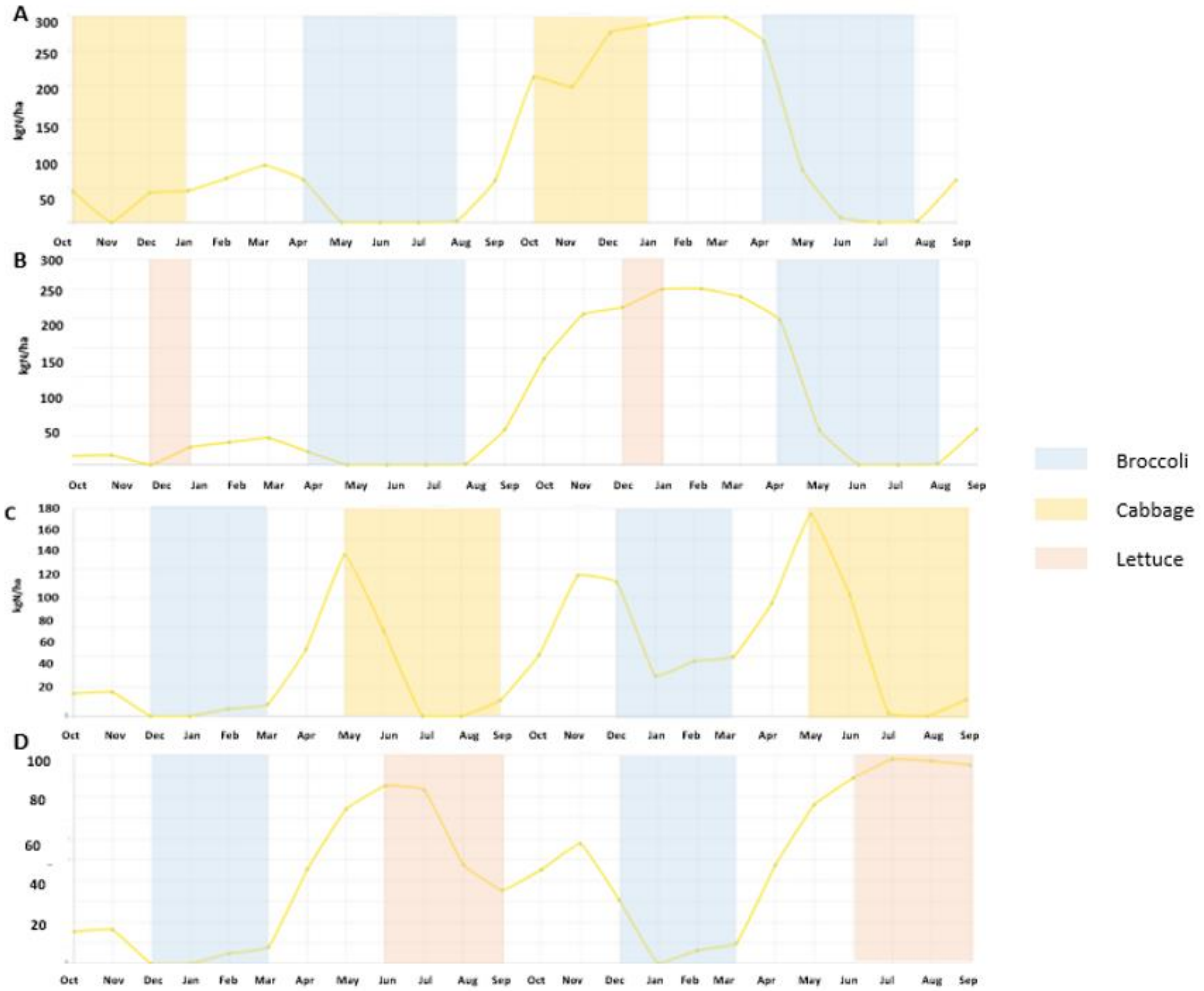

Figure 4.4 Monthly variations in the concentration of soil inorganic N across each of the broccoli scenarios. A=B-I-H, B=B-I-L, C=B-O-H, D=B-O-L.

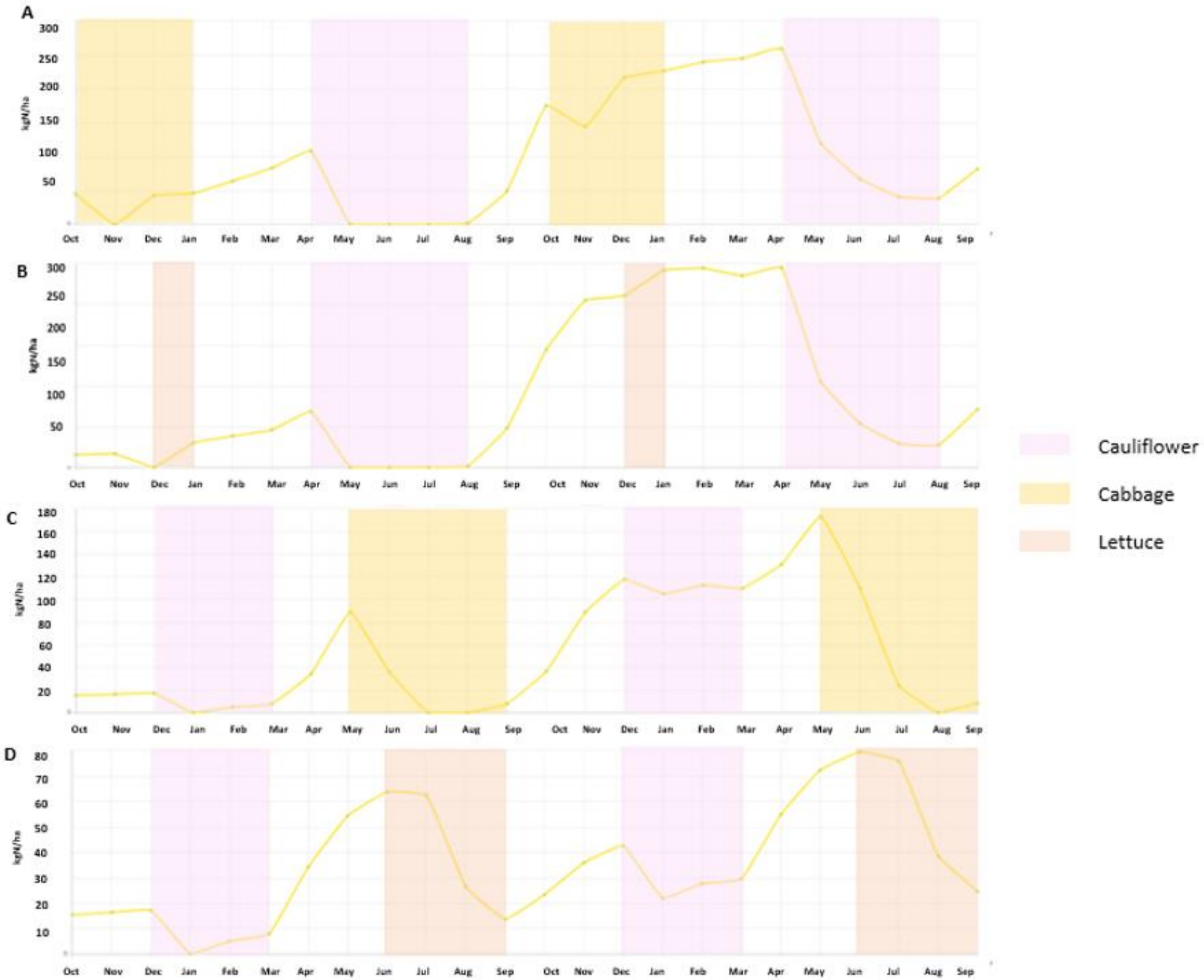

Figure 4.5 Monthly variations in the concentration of soil inorganic N across each of the cauliflower scenarios. A=C-I-H, B=C-I-L, C=C-O-H, D=C-O-L.

4.5.2 Concentration of Residue Nitrogen

Concentrations of residue N peak in the months following crop harvest (Figure 4.6A-D; Figure 4.7A-D). The scale of the increase varied between crops and growing seasons. The study crops tended to generate higher concentrations of residue N than the intervening cabbage and lettuce crops, except in scenarios B-O-H and C-O-H where the winter cabbage crop generated a peak concentration similar to the summer broccoli and cauliflower crops, respectively (Figure4.6C; Figure 4.7C). Furthermore, “in-season” rotations of the study crops tended to generate higher concentrations of residue N than “out-of-season” rotations of the study crops. Following the harvest of “in-season” (winter) broccoli in scenarios B-I-H and B-I-L, residue N increased to ~275 kg/ha, whereas following the harvest of “out-of-season” (summer) broccoli in scenarios B-O-H and B-O-L, residue N only increased to ~100 kg/ha (Figure 4.6A-D). Following the harvest of “in-season” (winter) cauliflower in scenarios C-I-H and C-I-L, residue N increased to ~225 kg/ha, whereas following the harvest of “out-of-season” (summer) cauliflower in scenarios C-O-H and C-O-L, residue N increased to only ~70 kg/ha (Figure 4.7A-D). As such, the variations in residue N between scenarios depicting “in-season” production and scenarios depicting “out-of-season” production appear to be most dependent on the season that the study crop was grown, most likely due to differences in yield (Table 3.7).

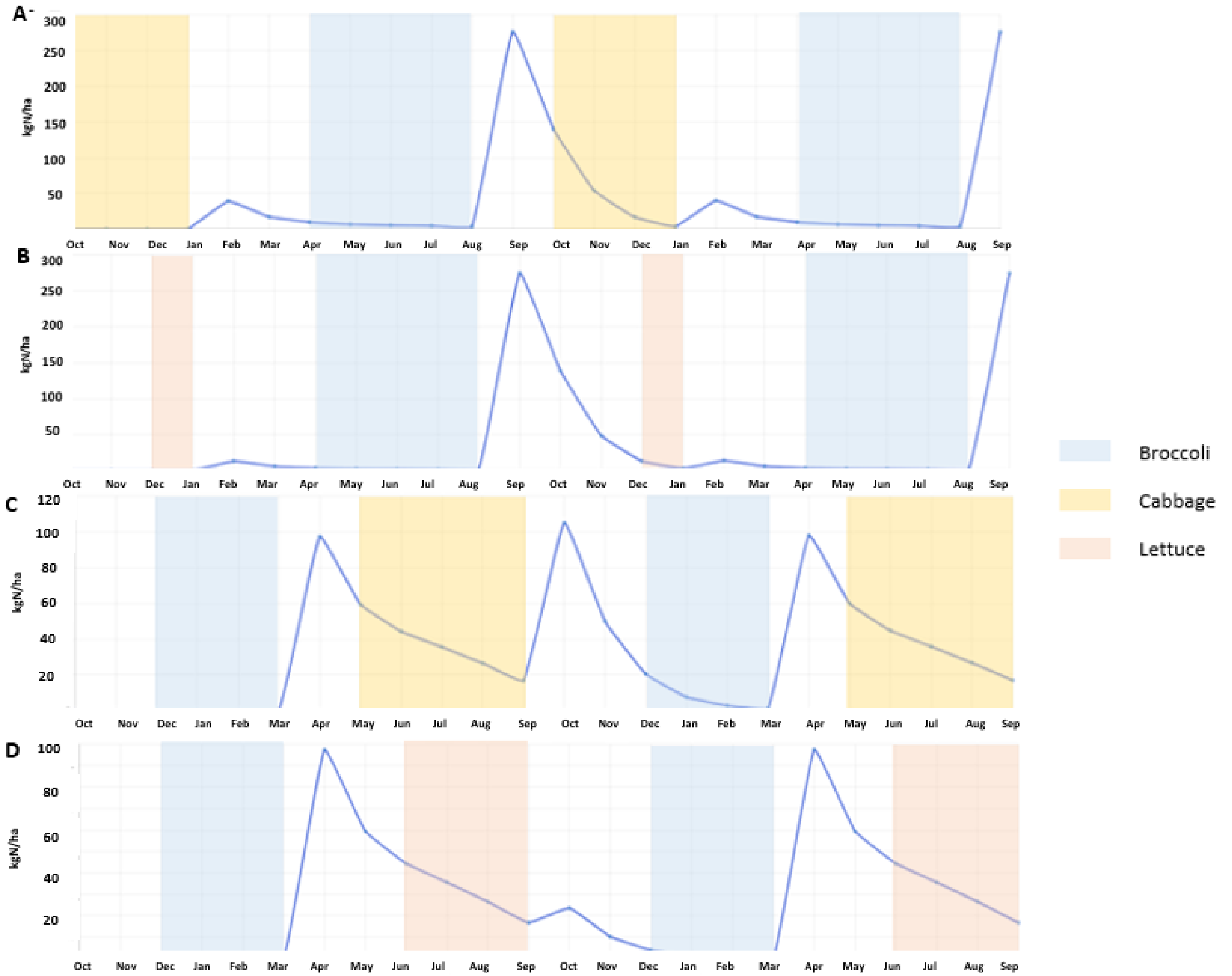

Figure 4.6 Monthly variations in the concentration of residue N across the broccoli scenarios. A=B-I-H, B=B-I-L, C=B-O-H, D=B-O-L.

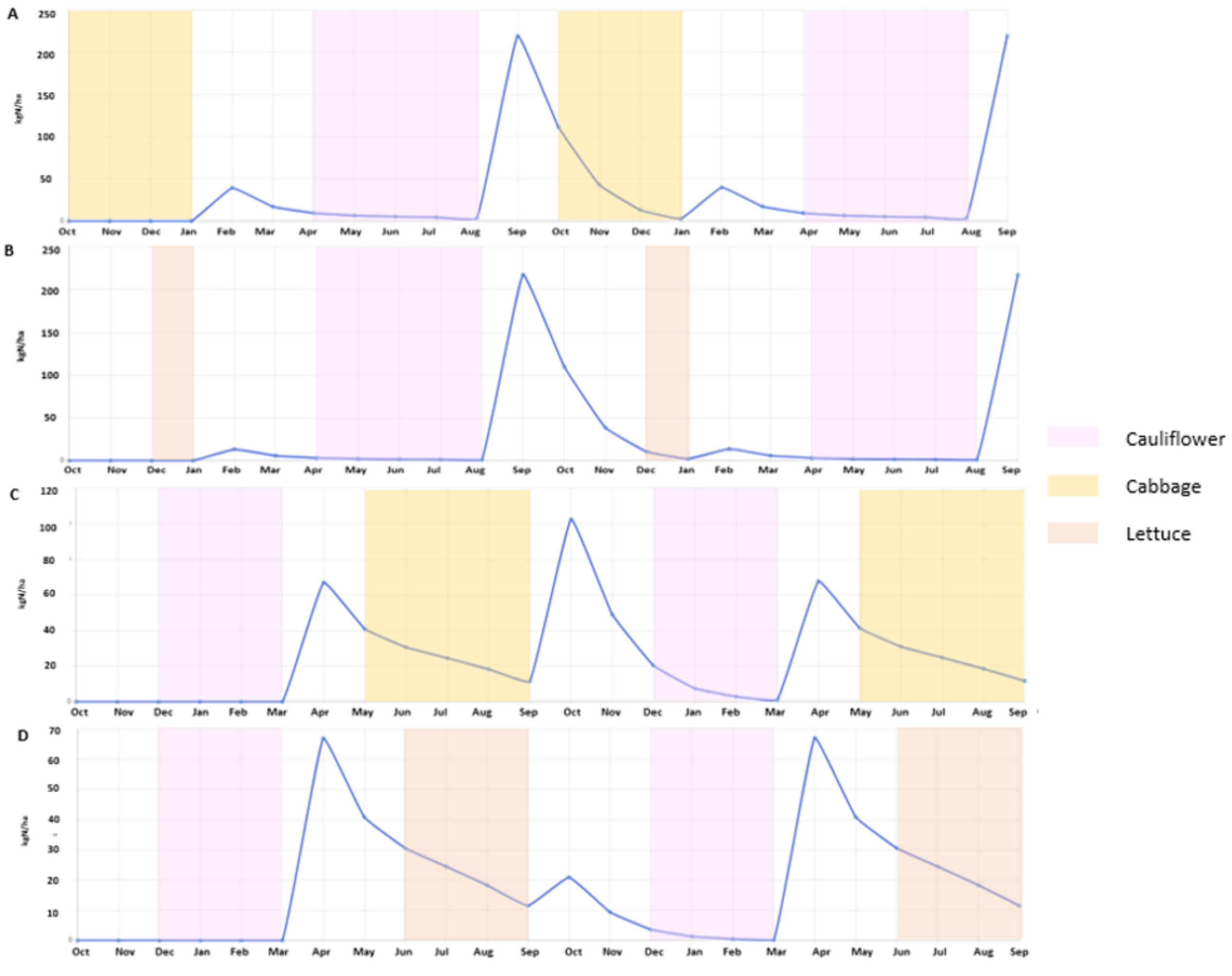

Figure 4.7 Monthly variations in the concentration of residue N across the cauliflower scenarios. A=C-I-H, B=C-I-L, C=C-O-H, D=C-O-L.

4.5.3 Rate of Nitrogen Mineralisation from Crop Residue

Rates of mineralisation of N from crop residue were very low or at zero, except in the months following crop harvest (Figure 4.8A-D; Figure 4.9A-D). They follow a very similar trend to the concentration of residue N (Figure 4.6A-D; Figure 4.7A-D). That is, following crop harvest, rates of N mineralisation increased (Figure 4.8A-D; Figure 4.9A-D). The peak rate of mineralisation typically occurred 1-2 months following crop harvest (Figure 4.8A-D; Figure 4.9A-D). The scale of the increase varied between crops and growing seasons. The study crops tended to generate higher rates of mineralisation than the intervening cabbage and lettuce crops, except in scenarios B-O-H and C-O-H, where the winter cabbage generated higher rates of mineralisation post-harvest than the summer broccoli and cauliflower (Figure 4.8C; Figure 4.9C). Furthermore, "in-season" rotations of the study crops tended to generate higher concentrations than "out-of-season" rotations of the study crops post-harvest. Following the harvest of "in-season" (winter) broccoli, mineralisation increased to ~140 kg N/ha/month, whereas following the harvest of "out-of-season" (summer) broccoli, residue mineralisation increased to only ~40 kg N/ha/month (Figure 4.8A-D). Following the harvest of "in-season" (winter) cauliflower in scenarios C-I-H and C-I-L, mineralisation increased to ~110 kg N/ha/month, whereas following the harvest of "out-of-season" (summer) cauliflower in scenarios C-O-H and C-O-L, residue N increased to only ~25-30 kg N/ha/month (Figure 4.9A-D). As such, variations in the rate of mineralisation appear to be heavily dependent on the season that the study crops are grown.

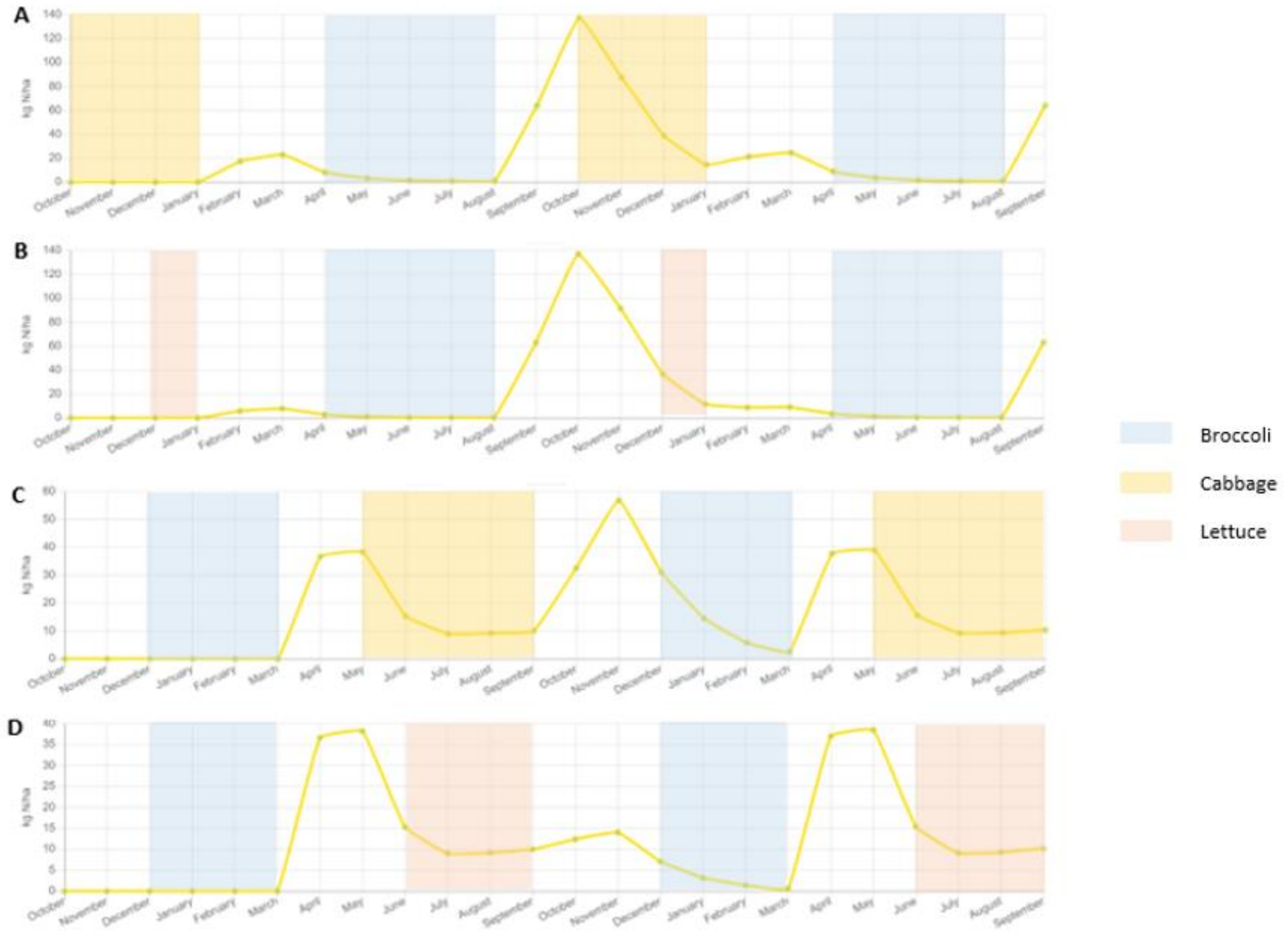

Figure 4.8 Monthly variations in the rate of mineralisation of N from crop residue across the broccoli scenarios. A=B-I-H, B=B-I-L, C=B-O-H, D=B-O-L.

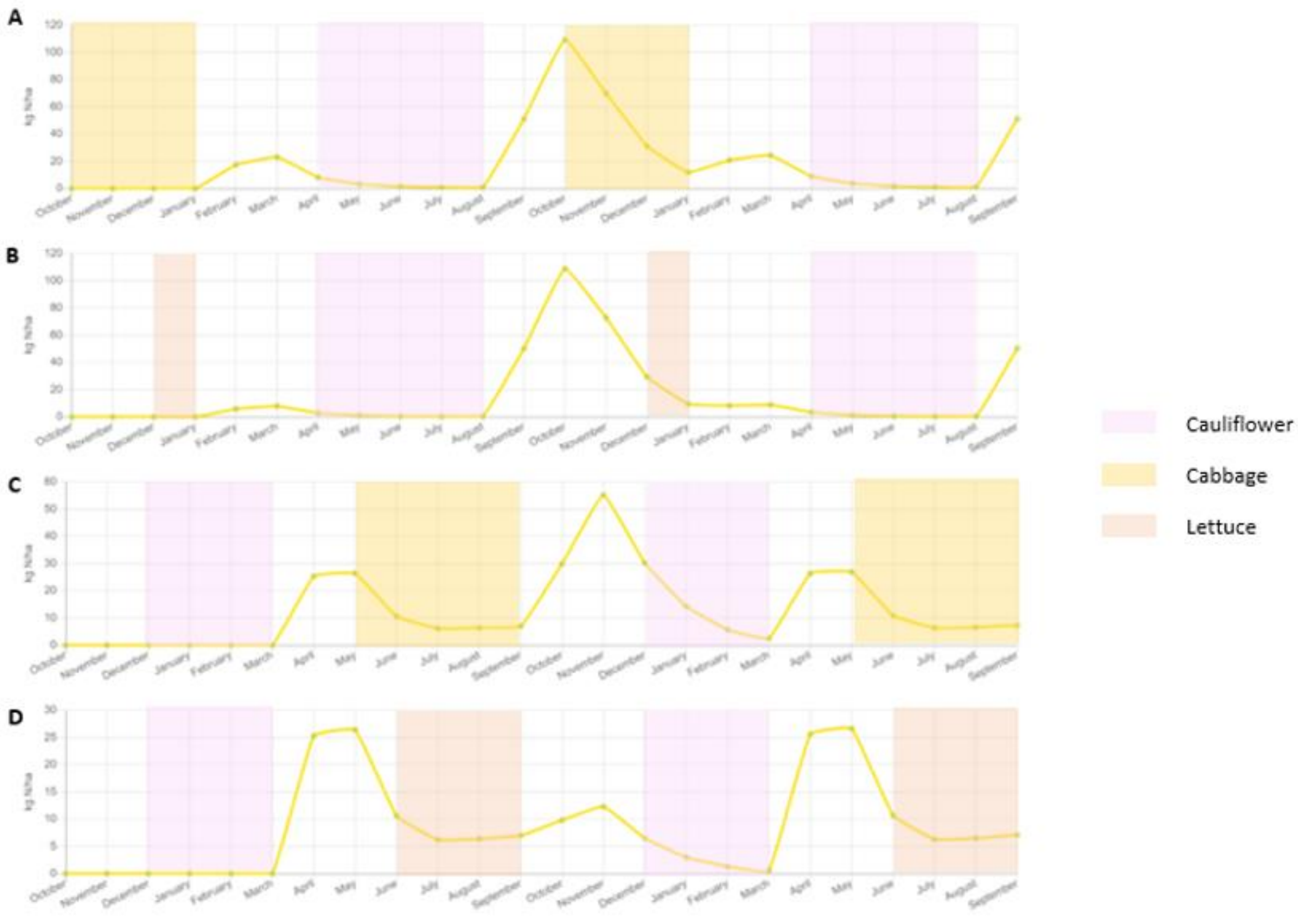

Figure 4.9 Monthly variations in the rate of mineralisation of N from crop residue across the cauliflower scenarios. A=C-I-H, B=C-I-L, C=C-O-H, D=C-O-L.

4.5.4 Rate of Plant Uptake

As expected, plant uptake peaked during periods of rapid crop growth. The magnitude of these peaks in plant uptake differed between crops and growing seasons. Both “in-season” (winter) broccoli and cauliflower had peak uptakes of ~200 kg N/ha/month, whereas “out-of-season” (summer) broccoli and cauliflower had peak uptakes of ~100 kg N/ha/month (Figure 4.10A-D; Figure 4.11A-D). The same trend was observed in cabbage, with respect to “in-season” crops taking up higher amounts of N. “In-season” (summer) cabbage had a peak uptake of ~175 kg N/ha/month, whereas ”out-of-season” (winter) cabbage had a peak uptake of ~120 kg N/ha/month (Figure 4.10A & C; Figure 4.11A & C). Lettuce was unique, as crops grown “in-season” and “out-of-season” both had peak uptakes of ~50 kg N/ha/month (Figure 4.10B & D; Figure 4.11B & D). There was one instance however where lettuce did not achieve this peak uptake. This was in the second lettuce crop grown in scenario B-O-L (Figure 4.10D). It is not clear why this is the case, as the management of this crop was the same as the lettuce crop grown in the previous year. These general findings however are explained by yield, as broccoli, cauliflower, and cabbage yields were higher in the “in-season” scenarios, and lettuce yields were the same irrespective of season (Table 3.7).

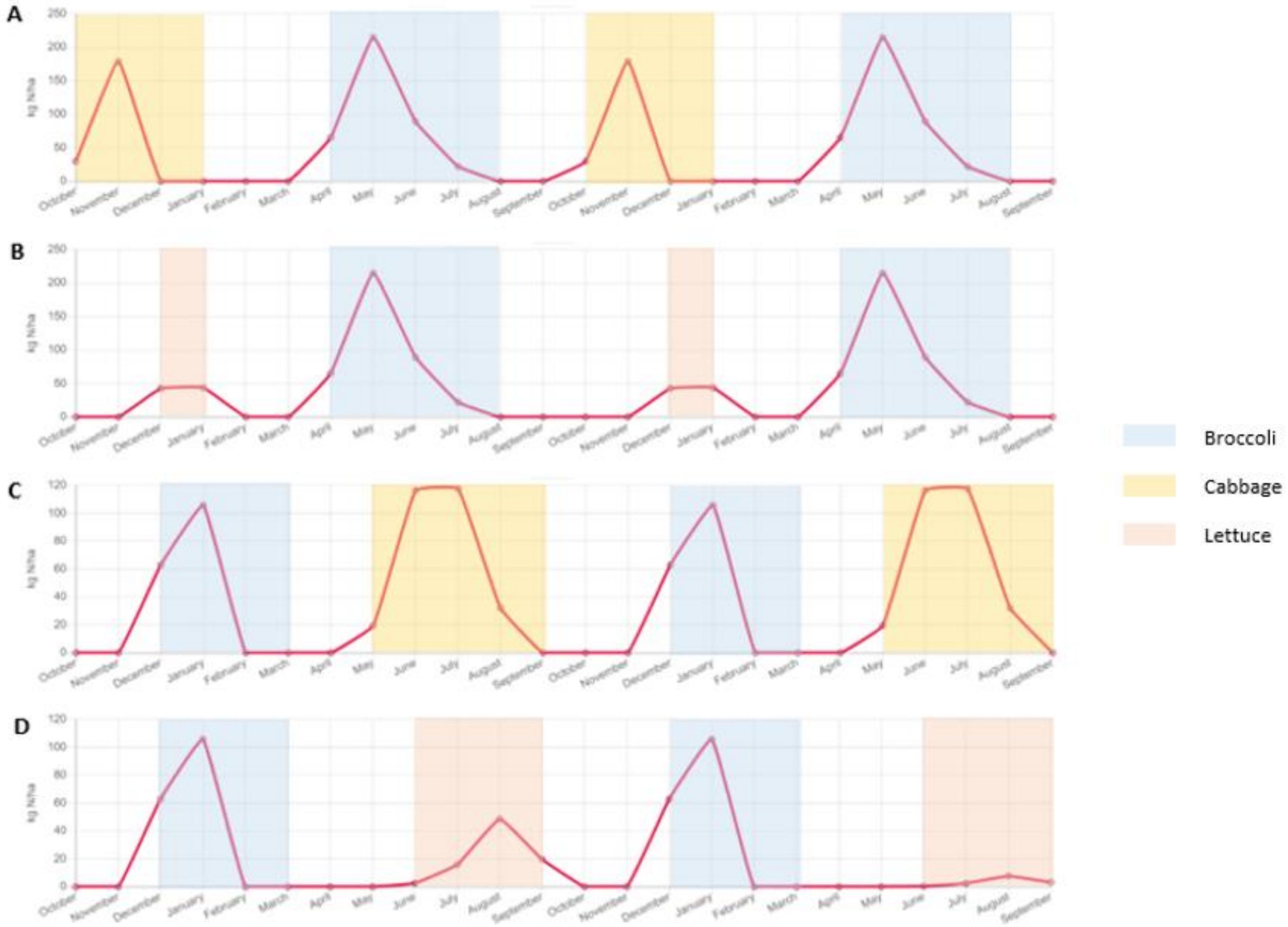

Figure 4.10 Monthly variations in plant uptake of N across the broccoli scenarios. A=B-I-H, B=B-I-L, C=B-O-H, D=B-O-L.

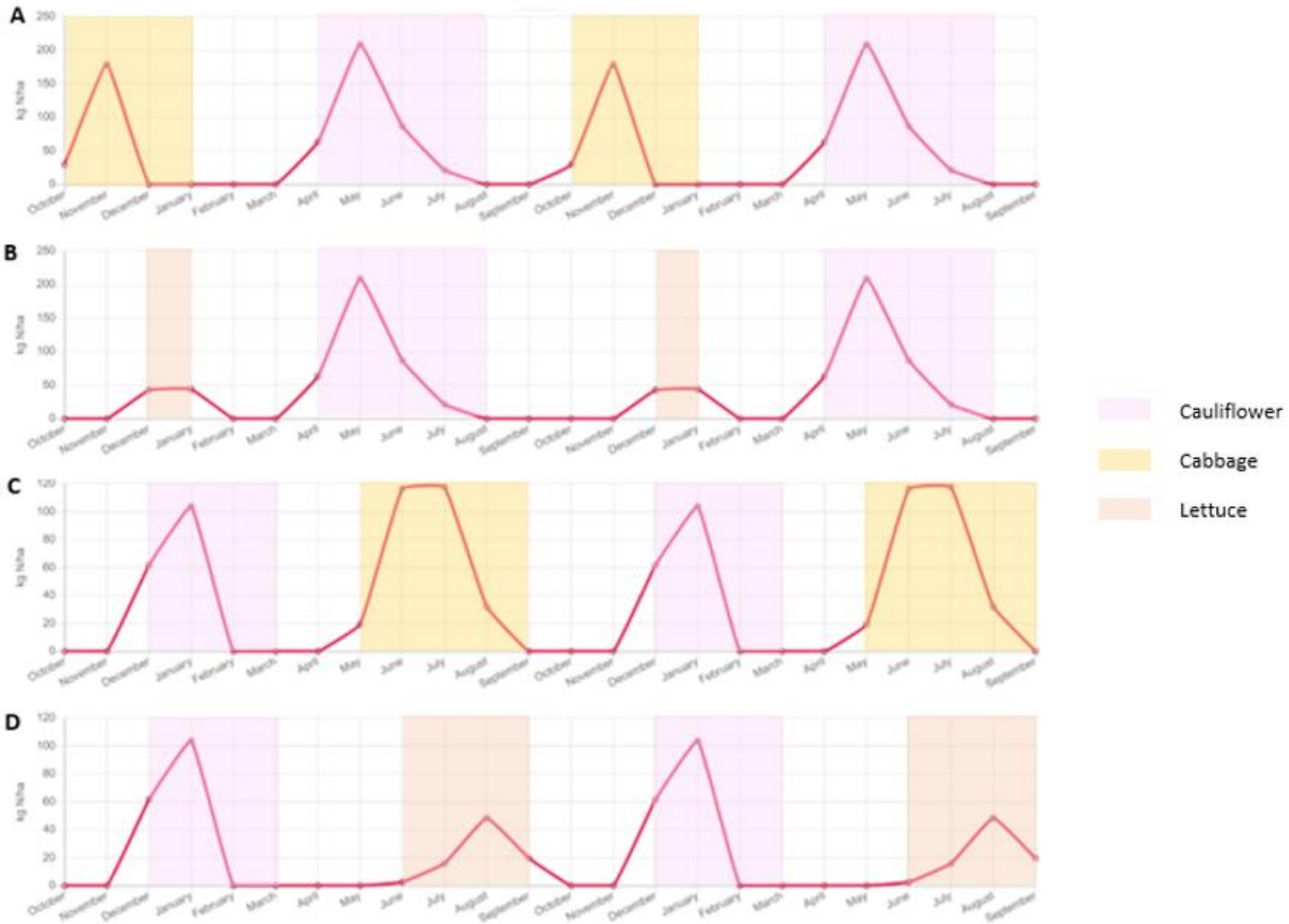

Figure 4.11 Monthly variations in plant uptake of N across the cauliflower scenarios. A=C-I-H, B=C-I-L, C=C-O-H, D=C-O-L.

4.6 Effect of the Intervening Crop on Nitrogen Leaching

In broccoli, the effect of changing the intervening crop on N leaching rates varied between the two models. It is not clear whether this was due to differences in the climate data used by each model (i.e. Overseer as a typical year and APSIM as 2019/2020), or other model intricacies, the consideration of which is beyond the scope of this thesis. Overseer estimated that the scenarios containing lettuce (i.e. low uptake crop) leached more N than those containing cabbage (i.e. high uptake crop) across both seasonal treatments (Table 4.1). In scenarios depicting "in-season" production, the scenario containing lettuce leached 7 kg N/ha more than the scenario containing cabbage, and in scenarios depicting "out-of-season" production, the scenario containing lettuce leached 23 kg N/ha more than the scenario containing cabbage (Table 4.1). The results from APSIM were less clear cut, as the effect of the intervening crop varied across the two seasonal treatments (Table 4.1). In scenarios depicting "in-season" production, the scenario containing lettuce leached 19 kg N/ha more than the scenario containing cabbage, but in scenarios depicting "out-of-season" production, the scenario containing cabbage leached 32 kg N/ha more than the scenario containing lettuce (Table 4.1). Hence, while there was a tendency by both models to estimate higher leaching rates in scenarios containing lettuce compared to scenarios containing cabbage, this was not consistent.

In cauliflower, the effect of the alternative crop on N leaching rates varied between the two models, and seasonal treatments. In each of the scenarios depicting "out-of-season" production, both APSIM and Overseer estimated higher leaching rates in scenarios containing cabbage than scenarios containing lettuce (Table 4.1). The leaching rates in scenarios containing cabbage were 19 kg N/ha and 15 kg N/ha higher than in scenarios containing lettuce in APSIM and Overseer, respectively (Table 4.1). The results across the scenarios depicting "in-season" production were more variable (Table 4.1). APSIM estimated that the leaching rate of the scenario containing lettuce was 16 kg N/ha higher than the scenario containing cabbage, and Overseer estimated the exact same leaching rate for both intervening crops (Table 4.1). Hence, the effect of the alternative crop was highly variable between the two models and seasonal treatments across the cauliflower scenarios. Given that no clear trend relating to the effect of the intervening crop on annual N leaching rates, the relationship will not be discussed further.

4.7 Effect of Good Management Practices on Nitrogen Leaching

4.7.1 Minimum Tillage

The use of minimum tillage cultivation instead of conventional cultivation reduced N leaching rates across all scenarios. Across the broccoli scenarios, Overseer estimated that N leaching rates were reduced by an average of 13% with the adoption of minimum tillage (Table 4.8). However, the effect varied considerably, with the estimated reductions ranging from 5-20% (Table 4.8). Across the cauliflower scenarios, Overseer estimated that N leaching rates were reduced by an average of 11% (Table 4.8). Again, the effect varied across scenarios, with the estimated reductions ranging from 8-18% (Table 4.8).

Table 4.8 Estimated reduction in N leaching rates under minimum tillage cultivation. Leaching rates are given for the reporting year.

Scenario	Leaching Rate (kg N/ha)		Reduction (%)	Average Reduction (%)
	Conventional (Original)	Minimum Tillage		
Broccoli				
B-O-H	42	40	5	13
B-O-L	65	52	20	
B-I-H	72	62	14	
B-I-L	79	67	15	
Cauliflower				
C-O-H	60	55	8	11
C-O-L	45	38	18	
C-I-H	89	82	8	
C-I-L	89	81	9	

4.7.2 Catch Crops

The inclusion of a catch crop reduced N leaching rates across all scenarios. Overseer estimated that on average, the inclusion of a catch crop reduced N leaching rates by 34% and 54% across the broccoli and cauliflower scenarios, respectively (Table 4.9). The magnitude of the reduction varied between the seasonal treatments. In "out-of-season" scenarios, which included a rotation of winter oats, N leaching rates were reduced by an average of 22% and 45% across broccoli and cauliflower scenarios, respectively (Table 4.9). Across the "in-season" scenarios, which included a rotation of maize, N leaching rates were reduced by an average of 45% and 63% across the broccoli and cauliflower scenarios, respectively (Table 4.9).

Table 4.9 Estimated reduction in N leaching rates with the inclusion of a catch crop. Leaching rates are given for the reporting year.

Scenario	Catch crop	Leaching Rate (kg N/ha)		Reduction (%)	Average Reduction (%)	Overall Average Reduction (%)
		No catch crop	Catch Crop			
Broccoli						
B-O-H	Oats	42	27	36	22	34
B-O-L		65	60	8		
B-I-H	Maize	72	41	43	45	
B-I-L		79	43	46		
Cauliflower						
C-O-H	Oats	60	21	65	45	54
C-O-L		45	34	24		
C-I-H	Maize	89	33	63	63	
C-I-L		89	33	63		

4.7.3 Comparison

Each of the GMPs explored here resulted in a reduction in N leaching (Table 4.10). Hence, their ongoing promotion and use within the vegetable cropping sector is supported by these results. Interestingly, Overseer perceives the reduction in N leaching under an “out-of-season” production regime compared to an “in-season” production regime to be comparable with the estimated reduction associated with the use of these GMPs (Table 4.10). Across the broccoli scenarios, “out-of-season” production yielded the second greatest average reduction in N leaching, and in cauliflower it yielded the second greatest average reduction in N leaching, equal to the inclusion of a forage oats catch crop (Table 4.10).

Table 4.10 Comparison of the average estimated reductions in annual N leaching between the modelled N GMPs with the average estimated reductions in annual N leaching achieved through “out-of-season” production.

Management Option	Average Reduction (%)		
	Broccoli	Cauliflower	Average
Minimum tillage	13	11	12
Inclusion of maize catch crop	45	63	54
Inclusion of winter oats catch crop	22	45	34
Producing “out-of-season” compared to “in-season”*	32	45	39

* Table 4.5 and Table 4.6.

4.8 Gross Margin Analysis

The effect of growing “in-season” was variable across the study and intervening crops (Table 4.11). In broccoli and cauliflower, the gross margins were higher for “in-season” production than for “out-of-season” production (Table 4.11). Specifically, the returns for “in-season” production were $5,970 and $14,440 greater for “in-season” production than “out-of-season” production in broccoli and cauliflower, respectively. In cabbage and lettuce, the gross margins were higher for “out-of-season” production than for “in-season” production (Table 4.11). Specifically, the returns for “out-of-season” production were $3,207 and $16,107 greater than for “in-season” production of cabbage and lettuce, respectively (Table 4.11). For reference, a full breakdown of the costs and returns calculated for each crop is available in Appendix C.

Table 4.11 Gross margins of individual crops.

Crop	Status	Gross Margin ($/ha/rotation)
Broccoli (summer)	Out-of-season	13,190
Broccoli (winter)	In-season	19,160
Cabbage (summer)	In-season	22,248
Cabbage (winter)	Out-of-season	25,455
Cauliflower (summer)	Out-of-season	8,844
Cauliflower (winter)	In-season	23,284
Lettuce (summer)	In-season	21,567
Lettuce (winter)	Out-of-season	37,674

Given the intensive nature of vegetable cropping in the Horowhenua, single rotations of vegetables are rarely grown in isolation, hence the modelling of "in-season" and "out-of-season" production as two-year scenarios. As such, it is necessary to look beyond the gross margins of individual crops when considering the long-term financial viability of a production regime. The consideration of the annual gross margin for each scenario on an annual scale helps to address this. Across both study crops, the "out-of-season" scenario alternated with lettuce (i.e., scenarios B-O-L and C-O-L) had the highest gross margin, and the "out-of-season" scenario alternated with cabbage (i.e., scenarios B-O-H and C-O-H) had the lowest gross margin (Figure 4.12). The gross margins of the "in-season" scenarios were placed between the minimum and maximum gross margins set by the "out-of-season" scenarios (Figure 4.12). Interestingly, the gross margins of the "in-season" scenarios were almost identical between the two intervening crops in both broccoli and cauliflower (Figure 4.12). This is because the "in-season" production of cabbage and lettuce have very similar gross margins (Table 4.11).

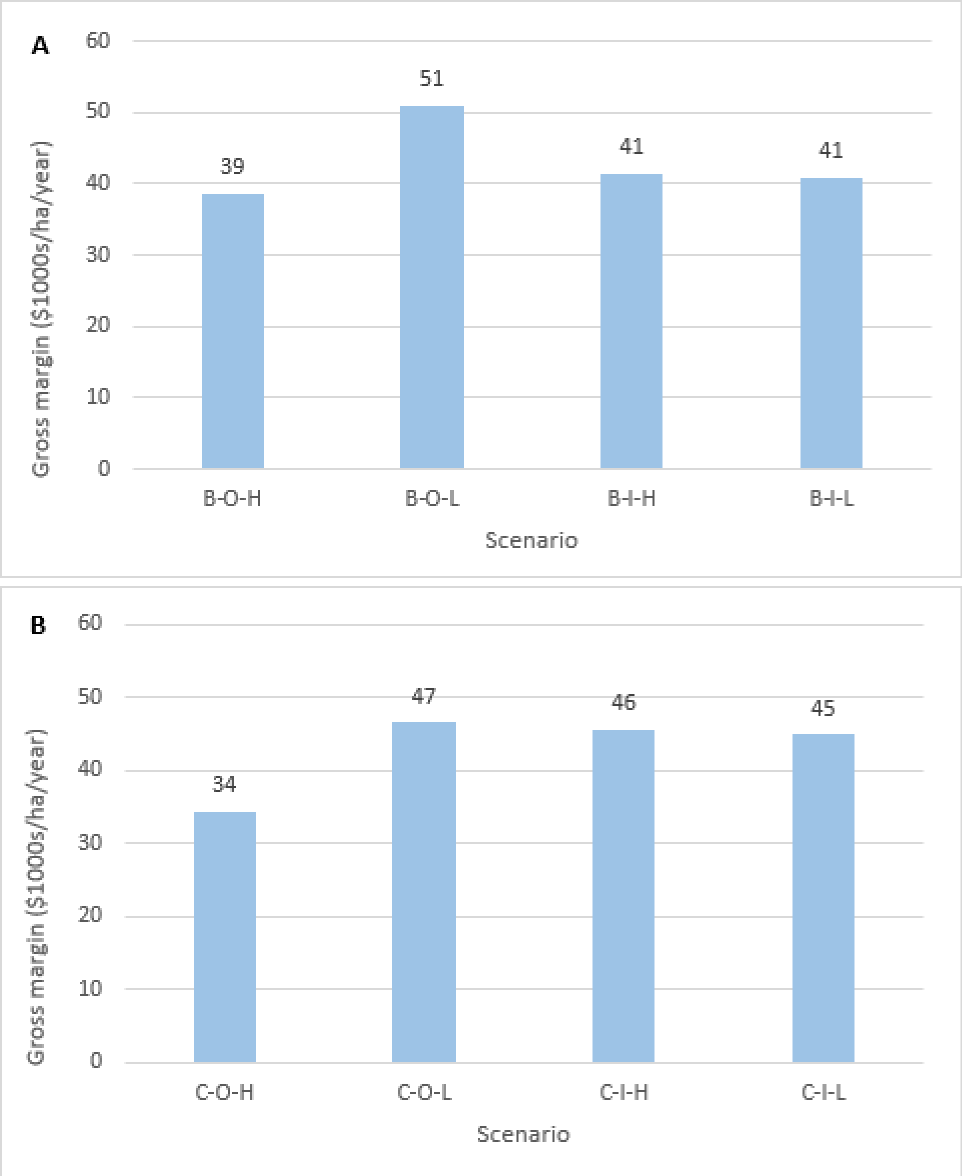

Figure 4.12 Gross margins for each of the (A) broccoli and (B) cauliflower scenarios.

5. Discussion

5.1 Leaching Rates

Jolly et al. (2020) modelled typical leaching rates under a broccoli and cauliflower crop rotation in the Horowhenua using Overseer. Their work provides a valuable point of comparison for the results presented here for the case study, as they modelled leaching rates under typical management practices, as well as a range of good N management practices. Under typical management, they reported a leaching rate of 220 kg N/ha/year (Table 2.1). Overseer generated leaching rates in the case study were considerably lower than this, as the highest estimated leaching rate under broccoli was 79 kg N/ha/year, and the highest leaching rate under cauliflower was 89 kg N/ha/year (Table 4.1). The leaching rates presented in this thesis are instead more consistent with the Jolly et al. (2020) estimates of leaching under a management regime utilising good fertiliser management practices. They estimated that under good fertiliser management, the leaching rate of the broccoli and cauliflower rotation was reduced to 123 kg N/ha (Jolly et al., 2020). Given that the case study aimed to utilise good nutrient management practices outlined by Reid & Morton (2019), this finding is not surprising. This does mean however, that it is likely that the magnitude and significance of any differences in leaching observed between "in-season" and "out-of-season" production in the case study will be different than what would be observed under more "typical" nutrient management.

5.2 Effect of Seasonal Production

Across both of the study crops, "in-season" production generated higher annual leaching rates (as kg N/ha) than growing "out-of-season". This finding was unanimous across both study crops and models used. Given that the two models used were different in terms of the type of year modelled (i.e., a typical year vs. an atypical year) and in terms of the processes used to model soil water and N dynamics (section 2.5), it reasonable to conclude that "in-season" production leaches more N in the context of the case study.

The finding that "in-season" production leaches more N than "out-of-season" production contradicts the popular narrative that growing crops "out-of-season" results in more N leaching than "in-season" production. However, a consideration of the leaching rates with respect to the yields produced in each scenario reveals that the "in-season" scenarios leached less N per unit of product than the "out-of-season" scenarios. In three of the four direct in-season vs. out-of-season comparisons in broccoli and cauliflower (e.g., B-I-H vs. B-O-H, etc), the "in-season" scenario is twice as efficient as the "out-of-season" scenario (Table 5.1). The exception was in B-I-L and B-O-L, where B-I-L was 1.6 times more efficient than B-O-L. Hence, while the "out-of-season" scenarios generally produced lower leaching rates per land area, the "in-season" scenarios were generally more efficient in the production of yield for every unit of N leached.

Table 5.1 N leaching rates per unit of product.

Scenario	Total Yield (t product/ha/year) *	N leached (kg N/ha/year) **	N leaching per yield unit (kg N leached/t product)
B-I-H	82	42	0.51
B-I-L	62	65	0.87
B-O-H	58	72	1.24
B-O-L	58	79	1.36
C-I-H	100	60	0.60
C-I-L	80	45	0.56
C-O-H	72	89	1.24
C-O-L	72	89	1.24

* Calculated from Table 3.7.

** From Table 4.1.

The implications of the differences in the efficiency of production with respect to the amount of N leached requires consideration. If it is assumed that consumer demand for the study crops remains constant throughout the year (an arbitrary 100 tonnes for simplicity), then the area needed to grow the study and intervening crops, and therefore the total N leaching under the study crops on vegetable farms in the Horowhenua can be compared. The results of this comparison suggest that there is potential for the demand for "out-of-season" production of the study crops to generate twice as much leaching compared to if the study crops were grown in season (Table 5.2). It is important to note that this is a very tentative analysis as it is based on the assumption of constant demand for the study crops throughout the year. If there is less demand for "out-of-season" produce, then the area growing these crops on Horowhenua farms would be smaller, as would N leaching. This is a twist to the debate about seasonal-based diets: advocates for eating in season may well have a point. To further this debate the exercise described in Table 5.2 needs to be conducted with more data and rigour.

Table 5.2 Illustration of the potential for the production of the study crops "out-of-season" to increase the land area needed for production, and total N leaching.

	Yield (t product/ha/year)	N leaching rate (kg N/ha/year)	Land area (ha) needed to produce 100 t of product	N leaching to produce 100 t of product
B-I-H	82	42	1.2	51
B-O-H	58	65	1.7	112
B-I-L	62	65	1.6	105
B-O-L	58	79	1.7	136
C-I-H	100	42	1	42
C-O-H	72	89	1.4	124
C-I-L	80	45	1.3	56
C-O-L	72	89	1.4	124

5.2.1 Processes

A large proportion of the annual leaching occurred over the autumn/winter period across all scenarios (Table 4.7). This contributed to the strong relationship between concentrations of soil inorganic N over this period and estimated annual leaching rates (Figure 4.3). As such, understanding how "in-season" and "out-of-season" production of the study and intervening crops influence soil inorganic N concentrations over this period is the key to understanding why the estimations of annual leaching rates in the "in-season" scenarios were higher than the estimations of leaching rates in the "out-of-season" scenarios.

In the "in-season" scenarios, concentrations of soil inorganic N over the autumn/winter period were higher than in the "out-of-season" scenarios (Figure 4.4A-D; Figure 4.5A-D). In the "in-season" scenarios, the crops grown immediately prior to the crucial autumn/winter leaching period, and hence the crops which might have been assumed to most directly have contributed to the high soil inorganic N concentrations over this period, were the intervening cabbage and lettuce crops (Figure 4.1A-D; Figure 4.2A-D). However, as the size of the soil inorganic N pool in the autumn/winter period was similar across both of the intervening crops, the soil inorganic N concentrations that accumulate over the autumn/winter period appear to be more heavily influenced by the crops grown in the previous winter than the intervening crops (Figure 4.4A-B; Figure 4.5A-B). As such, the discussion of the processes contributing to higher leaching in "in-season" scenarios will be further focused on the processes following the harvest of the winter broccoli and cauliflower crops which lead to high autumn/winter soil inorganic N concentrations.

Broccoli and cauliflower crops grown "in-season" (i.e., over winter) leave behind considerably more residue N than the broccoli and cauliflower crops grown "out-of-season" (Figure 4.6A-D; Figure 4.7A-D). This residue N decreases gradually over the spring and summer period to almost zero in January (Figure 4.6A-B; Figure 4.7A-B). Over the same period, there is a similar increase in inorganic N (Figure 4.4A-B; Figure 4.5A-B). This is largely explained by the high rates of mineralisation occurring over the summer, transforming organic N from the crop residue into inorganic N (Figure 4.8A-D; Figure 4.9A-D). Hence, the key driver behind the higher annual rates of N leaching in the "in-season" scenarios is the high amounts of residue left behind by the "in-season" (i.e., winter grown) broccoli and cauliflower. This is aligned with the findings from MacDonald et al. (1997) and Mai et al. (2010) outlined in section 2.2.3.2, that a large proportion of the N leached over the annual "peak" period of leaching, is derived from the mineralisation of N in crop residue. Hence, the findings from the case study are aligned with perspectives in wider literature.

The differences in the amount of residue N left behind between "in-season" and "out-of-season" broccoli and cauliflower crops are not proportional to differences in yield. "In-season" production of broccoli produces a 1.5 times greater yield than "out-of-season" production of broccoli, and "in-season" production of cauliflower produces 1.4 times greater yield than "out-of-season" production of cauliflower (Table 3.7). Yet, "in-season" production of broccoli produces a peak concentration of residue N ~2.75 times greater yield than "out-of-season" production of broccoli, and "in-season" production of cauliflower produces a peak concentration of residue N ~3.2 times greater than "out-of-season" production of cauliflower (Figure 4.6A-D; Figure 4.7A-D). Hence, Overseer obviously considers that there are factors other than the harvested yield driving the differences in residue N left behind between "in-season" and "out-of-season" crops.

5.2.2 Implications for Management

The key message from this analysis is that when seeking to reduce annual N leaching rates, it is essential to consider the timing and magnitude of peak concentrations of soil inorganic N. That is, to reduce the annual leaching rate, it is important to minimise concentrations of soil N during the autumn/winter period. As illustrated, this requires consideration of not just the crop grown in the preceding summer, but also of those grown in the preceding winter. Conversely, this means that elevated concentrations of soil inorganic N over the spring and summer period are typically less likely to increase the annual leaching rate, provided that the N is taken up by plants prior to the autumn/winter drainage period. However, it is important to note that summer drainage can occur. For example, a 100-year rainfall event in 2004 occurred in February, which is typically one of the region's driest months of the year (NIWA, 2018; Chappell, 2015). Hence, while maintaining lower soil inorganic N concentrations over summer is typically less critical than maintaining lower soil inorganic N concentrations over winter, especially on an annual basis, it is important to be aware of the potential for atypical rainfall events to generate leaching when least expected. APSIM will account for such events better than Overseer due to the use of yearly climate data, as was shown in September of the reporting year.

The finding that "out-of-season" production leached more N per unit of yield than "in-season" production requires the consideration of whether it is more desirable to manage N losses per unit of land area (i.e., kg N leached/ha) or in terms of N losses per unit of product (i.e., kg N leached/tonne product). This issue is common amongst N management strategies used in agricultural systems. For example, N leaching rates on dairy farms under organic management are generally lower than the leaching rates under conventional management (e.g., Knudsen et al., 2006; Kelly et al., n.d.). However, often so is the yield (e.g., Knudsen et al., 2006; Kelly et al., n.d.). Obviously, whether this point is given serious thought will depend on how different the N leaching rate is per unit yield under conventional management and under the use of relevant management approach. Given that the N leaching rate per unit of yield under "out-of-season" production was between 1.6 and 2 times higher than the N leaching rate per unit of yield under "in-season" production, the findings here seem worthy of further consideration (Table 5.2). However, given that most regulatory authorities currently regulate N leaching based on land area, not on the amount of product produced (e.g., Horizons Regional Council, 2018a), there would need to be a significant paradigm shift for this approach to be viable.

Given the heavy focus that regulatory authorities currently have on N leaching, it is necessary to consider the effect that seasonal production has on compliance with regulatory limits. Horizons Regional Council is in the process of increasing the N leaching limit on LUC class I land like the study block to 43 kg N/ha/year (Horizons Regional Council, 2018b). Based on Table 4.1, only scenarios B-O-H and C-O-L will comply with this limit, meaning that while "out-of-season" scenarios did foster a reduction in annual N leaching rates, that this reduction was not always enough to ensure regulatory compliance. Hence, even though producing the study crops "out-of-season" did generate impressive reductions in N leaching per unit of land area compared to producing the study crops "in-season", it is not a "silver bullet" approach with respect to solving the issue of non-compliance with N leaching limits on vegetable cropping farms.

As with any potential approach to environmental management, it is necessary to consider how "out-of-season" production of the study crops could affect other aspects of environmental health. Ayoola et al. (2009) suggest that the production of food "in-season" is generally more efficient than producing food "out-of-season", which could result in "out-of-season" production performing poorly in terms of other environmental performance indicators relating to resource use and climate change. Such concerns have been realised in several studies (e.g., Stoessel et al., 2012; Jungbluth et al., 2012). Although, Jungbluth et al. (2012) did find that eating "in-season" had the lowest relative benefit for mitigating climate change of a range of "environmentally friendly" diets, so it is unclear the extent to which "out-of-season" production might influence other environmental performance indicators like climate change.

5.2.3 Limitations

There are a number of limitations associated with applying the established relationship between "out-of-season" production and reduced rates of N leaching in a management context. Perhaps the most important is that this thesis has only tested the relationship between N leaching and seasonal production under good N management practices (i.e., Reid & Morton, 2019). Verbal reports of increased N leaching rates under winter, "out-of-season" production of lettuce, which motivated this research topic, suggested that growers will often "significantly increase the rate of N fertilisation over winter to increase the rate of growth", to ensure that they are able to meet the demand from the major supermarkets. Obviously, this research has not tested this, as to do this, typical fertiliser application rates would need to be obtained from growers. This avenue was explored at the beginning of this research project, but many growers refused to share such information in fear of recriminations from said supermarkets. As such, the true N leaching associated with "out-of-season" production under typical management has likely not been fully captured.

Another challenge associated with the extrapolation of the results of this thesis is the lack of clarity on what constitutes seasonal production. As mentioned, the terms "in-season" and "out-of-season" are not ones typically used by growers for the vegetables used in the case study (L. Posthuma, personal communication, 2021). Instead, the term is generally reserved for crops that can only be grown easily at certain times of the year, such as asparagus and sweetcorn (e.g., The Produce Company, 2021). Hence, in order for the practice to ever be discussed as a management approach for crops which are grown year-round, it would first be necessary to develop a simple definition of seasonal production, such as that outlined in section 2.6.1. However, as the yields of vegetable crops are so variable, as seen through the differences in the yields between APSIM and Overseer (Table 3.7), and those in Reid & Morton (2019), it is clear that even the use of the simple definition used in this thesis could create issues with the interpretation of when crops are "in-season".

Another limitation of the extrapolation of these findings is that the simple act of growing the study crops "out-of-season" has not driven the reductions in the annual leaching rate. Instead, they have been driven by the differences in the timing of various soil N parameters between "in-season" and "out-of-season" crops, as discussed in 5.2.1. These processes are likely to be different between crops, as the trends were largely driven by the high amounts of residue left behind by broccoli and cauliflower crops. As such, it is not possible to say whether "out-of-season" production would lead to lower N leaching rates than "in-season" in other crops, particularly those which leave behind less residue N or where "in-season" and "out-of-season" yields are more similar.

5.3 Alternative Management Practices

5.3.1 Minimum Tillage

The utilisation of minimum tillage reduced the rate of N leaching across both study crops. Tillage intensity and nitrate leaching have a strong positive association, as cultivation increases the rate of mineralisation of organic N from soil organic matter (Fraser et al., 2010). Given that the crops used in this thesis, especially broccoli and cauliflower, typically leave behind large amounts of soil organic N post-harvest, a reduction in N leaching under minimum tillage was expected (Figure 4.6A-D; Figure 4.7A-D).

Minimum tillage generally facilitated greater relative reductions in leaching in the “in-season” scenarios than in the “out-of-season” scenarios (Table 4.8). As the “in-season” scenarios had higher annual leaching rates than the “out-of-season” scenarios because of the high amounts of residue N left behind by the winter grown crop, there was more potential for a reduction in the rate of mineralisation of organic N to reduce soil inorganic N concentrations in the “in-season” scenarios (Fraser et al., 2010). As such, this result was expected.

5.3.2 Catch Crops

The effect of including a catch crop varied depending on the type of catch crop used. Across both study crops, maize was associated with a higher average reduction in N leaching than forage oats (Table 4.9). This is likely due to differences in the N uptake and timing of the two catch crops.

Maize has much higher N requirements than winter oats. Tsimba et al. (2020) measured N uptake in maize and forage oat catch crops and found that maize took up 187 kg N/ha more than oats. Even with the equivalent of 35 kg N/ha applied as fertiliser to maize, the net N deficit induced by maize is considerably higher than the N deficit induced by winter oats. Hence, maize has a higher potential to reduce inorganic N levels in soil, and hence to reduce the potential for N leaching.

Maize and forage oats are grown at different times of the year. Given the established relationship between soil inorganic N concentrations in autumn/winter and the rate of annual N leaching, the timing of the growth, and hence the reductions in soil inorganic N induced by each of the study crops, is an important factor to consider. In both study crops, maize was established in November (Table 3.9; Table 3.10). Given the strong association between annual leaching rates and the average concentration of inorganic N in autumn/winter, this means that the reductions in inorganic N induced by maize are timed at the ideal time of year to facilitate a reduction in annual N leaching. In contrast, forage oats are established in May. Given that May is often the peak month for N leaching in Overseer, and that accumulation of biomass and N in the first weeks of growth in forage oats is typically very low, it is unlikely that the forage oats will prevent elevated inorganic N from being leached in the year they are grown (Horrocks et al., 2009; Figure 4.1A-D, Figure 4.2A-D). However, the oats will eventually reduce elevated soil inorganic N concentrations, which will have benefits in the following autumn/winter period, as is represented by the reductions shown in Table 4.8, even though the forage oats were included in year one (Table 3.9; Table 3.10).

5.3.3 Comparison

The reduction in N leaching estimated under "out-of-season" production was comparable to the reductions achieved through the use of minimum tillage and catch crops. Given that the use of minimum tillage and catch crops are reputable N management techniques, this adds substantial weight to the results. However, as mentioned, it was not the simple act of producing crops "out-of-season" that generated the reductions in N leaching; it was the timing of soil inorganic N with respect to the autumn/winter leaching period, as influenced by the timing of elevated residue N concentrations and hence the mineralisation of N from crop residue. Hence, the practical use of these findings will require a strong understanding of the N dynamics of different crops. As such, using "out-of-season" to reduce N leaching rates will likely never be able to be communicated as simply as the use minimum tillage or catch crops.

As with any environmental management approach, there are difficulties associated with the adoption of minimum tillage and the use of catch crops. These difficulties may be practical, or financial. In the case of minimum tillage, there may be practical difficulties such as achieving good seeding and disease and weed control (Shrestha et al., 2006; Lane et al., 2013). In the case of catch crops, there may be financial difficulties as they are generally worth less than commercial vegetable crops (e.g., The AgriBusiness Group, 2014b). Hence, while the use of "out-of-season" production to reduce N leaching rates would likely encounter practical difficulties, including the communication of the considerations that need to be made, this is also true of widely used N management practices in the sector.

5.4 Gross Margin Analysis

The AgriBusiness Group (2014b) performed a gross margin analysis of an intensive vegetable cropping operation in the Horowhenua and provide a valuable point of comparison for the gross margins presented in Table 5.2. The gross margins calculated for individual crops in this report were 1.4-4.9 times higher than those calculated by the AgriBusiness Group (2014b). Given that many of the costs used to calculate the gross margins in this report were derived from their analysis, these differences will be due to differences in the revenue calculated for each crop, and by the inclusion of different expenses (Table 3.11). In general, the Agribusiness Group (2014b) analysis assumed much lower returns per unit yield than this analysis. This is not unexpected, given the age of their analysis. However, even when accounting for inflation, the prices in this thesis are still on average much higher (Appendix C). This could be for a number of reasons, including an underestimation of the average retail mark-up, or if the prices used were from an abnormally "good" year for growers. One key difference between the calculation of expenses between this report and the Agribusiness Group (2014) report was the inclusion of land lease costs. In this thesis, land lease costs were not included, but in the AgriBusiness Group (2014b) analysis, an average lease cost of $1,875/ha/crop rotation, equivalent to ~$2,000/ha/crop rotation when accounting for inflation, was included. Hence, there are several potential reasons why the values generated by the gross margin analysis in this thesis were higher compared to their analysis.

Table 5.3: Comparison of gross margins from this report with those by the AgriBusiness Group (2014b).

Crop	This thesis	AgriBusiness Group (2014b)
	Gross Margin ($/ha/rotation)	
Broccoli (summer)	13,190	3,923
Broccoli (winter)	19,160	Not calculated
Cabbage (summer)	22,248	Not calculated
Cabbage (winter)	25,455	5,157
Cauliflower (summer)	8,844	3,820
Cauliflower (winter)	23,284	Not calculated
Lettuce (summer)	21,567	7,282
Lettuce (winter)	37,674	Not calculated

5.4.1 Limitations

There were a number of limitations associated with the gross margin analysis approach used. Firstly, the differential costs and returns of each crop were calculated solely on the differences in yield between the growing seasons of each crop. That is, if the summer crop had a higher yield than the winter crop, then the returns and production costs of the summer crop would both be higher relative to the winter crop. However, this likely does not accurately account for the differences in costs and returns of growing seasonally. For example, it is likely that peak "in-season" production will be more cost efficient per unit of yield (e.g., Ayoola et al., 2009). In addition, due to the higher retail costs typically associated with purchasing produce "out-of-season", there can often be lower consumer interest and demand, leaving the crop unsold.

Conversely, when producing in-season, there may be an excessive supply of produce, which may also leave the crop unsold. This failure to sell could occur either pre-harvest or post-harvest. None of these factors have been accounted for, as the analysis assumes that the yield is achieved, and that this yield is able to be sold. To accurately account for these factors, considerable amounts of data would need to be obtained from growers, and a considerably more complex analysis would be required. Hence, no firm conclusions can be drawn from this gross margin analysis. Given the severity of these limitations and the disparity between the calculated values in this thesis and those produced in similar analyses, it is not possible to draw conclusions from the results of the gross margin analysis.

6. Conclusions

N leaching rates under intensive vegetable cropping are high compared to other intensive land uses. There is an increasing urgency to reduce N leaching under vegetable cropping to improve regulatory compliance and to maintain a social license to operate. It has been claimed that "out-of-season" production of vegetables exacerbates these already high N leaching rates. This thesis investigated this claim to determine whether growing vegetables "in-season" could reduce N leaching under intensive vegetable cropping.

A case study cropping block in the Horowhenua was used to explore the research question. The effect of "out-of-season" production on N leaching rates was assessed by developing a range of scenarios depicting "in-season" and "out-of-season" production of the study crops. The case study was analysed using both APSIM and Overseer. This allowed the effect of seasonal production on trends in N leaching in a) a typical year (Overseer), and b) in an atypical year (APSIM), with respect to climate, to be compared. Although, due to the differences in the interpretation of soil water and N dynamics between the two models, not all observed differences could be attributed to the differences in climate between the two years modelled.

The results found that N leaching rates (as kg N/ha) under "out-of -season" production were lower than under "in-season" production. The average estimated reduction under "out-of-season" production was 32% and 45% in the broccoli and cauliflower scenarios, respectively. This difference was attributed to the generation of greater concentrations of soil inorganic N over the autumn/winter period under "in-season" production of broccoli and cauliflower. This was driven by higher concentrations of residue N following the harvest of the high-yielding "in-season" rotations. As good nutrient management practices were used in the case study, it is not possible to extrapolate these findings to systems which do not utilise good nutrient management.

While the annual leaching rates of N leaching (as kg N/ha) were lower under "out-of-season" production, "out-of-season" production was much less efficient in terms of the amount of N leached per tonne of product produced than "in-season" production. This is because the reductions in N leaching achieved through "out-of-season" production were not proportional to the reductions in yield. As such, whether "out-of-season" production is better or worse for N leaching depends on the perspective taken.

The reductions in annual N leaching achieved through "out-of-season" production were comparable to the reductions estimated following the adoption of minimum tillage and catch crop GMPs. This supports further research and development of timing-based crop management approaches such as seasonal production in the vegetable cropping industry.

The gross margin analysis indicated that the financial returns associated with “in-season” and “out-of-season” production varied depending on the intervening crop included in the rotation schedule. Due to the limitations of the approach taken however, it was not possible to draw any definitive conclusions about the financial viability of either an “in-season” or “out-of-season” vegetable production regime.

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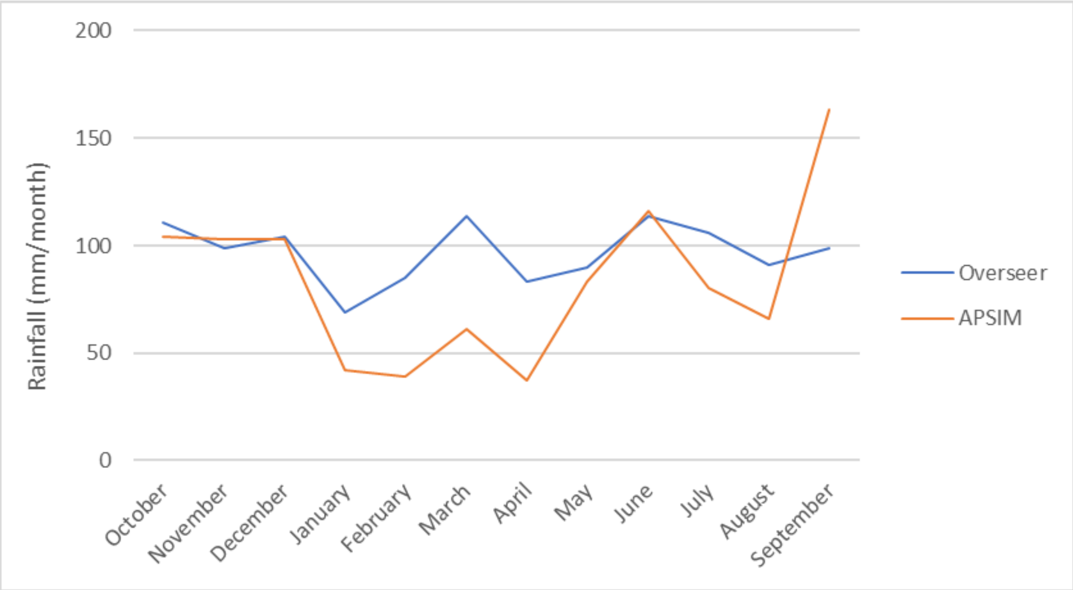
Appendix A

Monthly rainfall data used by Overseer and APSIM. Note that the data plotted for Overseer is not the exact monthly rainfall distribution used by Overseer, as this information is not user accessible. Instead, it is long term monthly averages from Chappell (2015) as this will be a close replicate. The data plotted for APSIM is the actual data used and is from the 2019/2020 period.



Appendix B

Schedule of fertiliser applications.

Time		Scenario			
Month	**Year**	**B-I-H**	**B-I-L**	**B-O-H**	**B-O-L**
Oct	1	161 kg/ha YMC + 147 kg/ha CAN			
Nov	1	2 x 147 kg/ha CAN			
Dec	1	1 x 147 kg/ha CAN	161 kg/ha YMC	103 kg/ha YMC + 47 kg/ha CAN	103 kg/ha YMC + 47 kg/ha CAN
Jan	1		3 x 86 kg/ha CAN	2 x 47k g/ha CAN	2 x 47k g/ha CAN
Feb	1				
Mar	1				
Apr	1	151 kg/ha YMC + 69 kg/ha CAN	151 kg/ha YMC + 69 kg/ha CAN		
May	1	2 x 69 kg/ha CAN	2 x 69 kg/ha CAN	231 kg/ha YMC + 106 kg/ha CAN	
Jun	1	1 x 69 kg/ha CAN	1 x 69 kg/ha CAN	2 x 106 kg/ha CAN	71 kg/ha YMC
Jul	1			1 x 106 kg/ha CAN	2 x 32 kg/ha CAN
Aug	1				1 x 32 kg/ha CAN
Sep	2				
Oct	2	161 kg/ha YMC + 147 kg/ha CAN			
Nov	2	2 x 147 kg/ha CAN			
Dec	2	1 x 147 kg/ha CAN	161 kg/ha YMC	103 kg/ha YMC + 47 kg/ha CAN	103 kg/ha YMC + 47 kg/ha CAN
Jan	2		3 x 86 kg/ha CAN	2 x 47 kg/ha CAN	2 x 47k g/ha CAN
Feb	2				
Mar	2				
Apr	2	151 kg/ha YMC + 69 kg/ha CAN	151 kg/ha YMC + 69 kg/ha CAN		
May	2	2 x 69 kg/ha CAN	2 x 69 kg/ha CAN	231 kg/ha YMC + 106 kg/ha CAN	
Jun	2	1 x 69 kg/ha CAN	1 x 69 kg/ha CAN	2 x 106 kg/ha CAN	71 kg/ha YMC
Jul	2			1 x 106 kg/ha CAN	2 x 32 kg/ha CAN
Aug	2				1 x 32 kg/ha CAN
Sep	2				

Time		Scenario			
Month	**Year**	**C-I-H**	**C-I-L**	**C-O-H**	**C-O-L**
Oct	1	161 kg/ha YMC + 147 kg/ha CAN			
Nov	1	2 x 147 kg/ha CAN			
Dec	1	1 x 147 kg/ha CAN	161 kg/ha YMC	161 kg/ha YMC + 142k g/ha CAN	161 kg/ha YMC + 142k g/ha CAN
Jan	1		3 x 86 kg/ha CAN	2 x 142 kg/ha CAN	2 x 142 kg/ha CAN
Feb	1				
Mar	1				
Apr	1	337 kg/ha YMC + 155 kg/ha CAN	337 kg/ha YMC + 155 kg/ha CAN		
May	1	2 x 155 kg/ha CAN	2 x 155 kg/ha CAN	231 kg/ha YMC + 106 kg/ha CAN	
Jun	1	1 x 155 kg/ha CAN	1 x 155 kg/ha CAN	2 x 106 kg/ha CAN	71 kg/ha YMC
Jul	1			1 x 106 kg/ha CAN	2 x 32 kg/ha CAN
Aug	1				1 x 32 kg/ha CAN
Sep	2				
Oct	2	161 kg/ha YMC + 147 kg/ha CAN			
Nov	2	2 x 147 kg/ha CAN			
Dec	2	1 x 147 kg/ha CAN	161 kg/ha YMC	161 kg/ha YMC + 142k g/ha CAN	161 kg/ha YMC + 142k g/ha CAN
Jan	2		3 x 86 kg/ha CAN	2 x 142 kg/ha CAN	2 x 142 kg/ha CAN
Feb	2				
Mar	2				
Apr	2	337 kg/ha YMC + 155 kg/ha CAN	337 kg/ha YMC + 155 kg/ha CAN		
May	2	2 x 155 kg/ha CAN	2 x 155 kg/ha CAN	231 kg/ha YMC + 106 kg/ha CAN	
Jun	2	1 x 155 kg/ha CAN	1 x 155 kg/ha CAN	2 x 106 kg/ha CAN	71 kg/ha YMC
Jul	2			1 x 106 kg/ha CAN	2 x 32 kg/ha CAN
Aug	2				1 x 32 kg/ha CAN
Sep	2				

Appendix C

Gross margin analysis calculation

	Broccoli (summer)	Broccoli (winter)	Cabbage (summer)	Cabbage (winter)	Cauli (summer)	Cauli (winter)	Lettuce (summer)	Lettuce (winter)
				Revenue				
Yield (t/ha)	8	12	70	50	22	30	50	50
Price ($/t)	3148	2915	845	1112	1399	1760	1574	1910
Sum	**25186**	**34980**	**59127**	**55612**	**30782**	**52788**	**78696**	**95485**
				Expenses				
Cultivation	1232	1232	2987	2987	1161	1161	3260	2160
Seed	347	346.5	1552	1552	2970	2970	2905	2905
Agri-chemicals	1870	1870	1198	1198	605	605	1198	1198
Fertiliser	696	969	1005	1317	935	1446	823	619
Irrigation	151	0	123	0	151	0	104	0
Harvest	1333	2200	1650	1179	1815	2475	9075	9075
Grading	0	0	1650	1179	0	0	9075	9075
Packing	1210	1815	1650	1179	4907	6691	8250	8250
Freight	2024	3036	17710	12650	5566	7590	12650	12650
Drying	0	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Storage	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
Commission	3022	4198	7095	6673	3694	6335	9444	11458
Levies	111	154	260	245	135	232	346	420
Sum	**11996**	**15820**	**36880**	**30157**	**21938**	**29504**	**57130**	**57811**
Gross margin ($/ha)	13190	19160	22248	25455	8844	23284	21567	37674