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The effects of post-harvest management on the
seed yield of a tall fescue (*Festuca
arundinacea*) seed crop

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Abstract

Tall fescue seed crops require post-harvest residue management to prepare the crop for the following season. Previously farmers relied on methods such as burning residue, but due to a change in social license around air quality and public safety concerns, there has been a reduction in this management practice. The objective of this research was to investigate non-thermal post-harvest residue management practices required to maximise seed yield for a tall fescue seed crop with full post-harvest straw load retained. Two experiments were conducted on a crop of tall fescue (cv. *Volupta*) entering its third year of seed production. Trial 1 showed that in the absence of grazing, the most effective method of residue management was to leave the crop stubble at a post-harvest height of 14 cm, and to mow the crop either under a frequent (monthly) or lax (once at closing) regime. The frequency of the mowing treatments had no effect on seed yield. These treatments produced an average seed yield of 435 kg/ha. Trial 2 showed that under grazing, seed yields were highest in plots left with 14 cm of stubble after harvest, with an average seed yield of 327 kg/ha. Spring nitrogen applications in the grazed trial had no effect on final seed yield. The lower seed yield in the cutting to 7 cm and nil cut treatments, was a result of a lower number of fertile tillers. For the former, cutting removed all of the leaf tissue, while in the latter, plants were shaded. Both reduced the leaf surface area for photosynthesis and therefore the ability to support tiller initiation and growth. This in turn reduced the final seed yield of the crop and showed the most effective management practice is to leave the crop at 14 cm and mow frequently or laxly.

Keywords: Seed production, tiller production, grazing, nitrogen, cutting

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Chapter 1.

Introduction

New Zealand exports herbage seed to over 40 different countries worldwide. The species exported are dependent on world prices and demand. Although small, New Zealand is very competitive on a global scale. One reason for this is because New Zealand is able to produce high yielding seed crops at relatively low costs per kilogram (kg) of dressed seed (Rolston et al., 1990). Through the seed certification scheme the genetic and physical purity of New Zealand produced seed is assured. New Zealand also has a well-established research and technology base enabling adaptation to keep up with global trends.

The domestic herbage seed industry is also well known for producing both annual and perennial seed crops. Perennial seed crops require different management practices than annual seed crops due to the residue left on the paddock post-harvest. This residue or “trash” as it is sometimes referred to needs to be removed from the system to allow the crop underneath to recover and produce seed for the following year. This makes perennial seed crops more difficult to grow but does have economic benefits because the crop does not have to be resown the following year.

Tall fescue (*Festuca arundinacea*), a perennial pasture and turf species originally descending from Europe is grown throughout New Zealand for forage. It is also grown in Oregon for the commercial turf market. Tall fescue is easily identifiable by its wide leaves with prominent parallel veins. It is a continental C3 pasture species. A C3 plant is one that initially produces 3-phosphoglycerate during carbon dioxide assimilation, containing three carbons (Liang et al., 2012). In recent times tall fescue has increased in popularity as a resilient pasture plant. This is due to its wider tolerance for environmental extremes that the more commonly sown perennial ryegrass (*Lolium perenne*) struggles to persist through (Mohlenbrock, 2002). It is frequently sown in dryland systems, as tall fescue has a deeper rooting system that allows for better access to water lower in the soil profile than other pasture species (Callow et al., 2003). Tall fescue also persists in areas of low fertility, that

often accompany low moisture regions, such as in parts of Australia (Easton et al., 1994). Tall fescue seed production commonly occurs in Oregon as well as New Zealand. In Oregon tall fescue seed production increased from 4000 ha in 1979 to more than 57000 ha in 2004 (Rolston and Young, 2009). In 2003 global exports reached of 84,200 tons of tall fescue seed. New Zealand contributed to 0.8% of this (Brock et al., 1982).

Tall fescue is established in wide 30-60cm rows due to the dense structure of the plant (Chastain et al., 2000). Sowing date is highly influential in determining final seed yield. Hare (1994) found that a tall fescue crop sown on the 4th of March produced 91707 seeds per m² compared with a crop sown on the 15th of April that only produced 28112 seeds per m². This is because on average 92% of the tillers are formed in the autumn period for vernalisation to occur over winter (Hare, 1994). When the sowing date is delayed in autumn, more of the tillers in the sward would remain vegetative due to the lack of vernalisation, reducing the final seed yield. Typically sowing rates of 20kg/ha or below are recommended as tall fescue seed crops become very dense (Hickey, 1990), therefore reducing light interception by the canopy of the plant and the light penetration to the crown. Tall fescue requires a readily available supply of nitrogen, phosphorous, potassium and sulphur to produce high seed yields. Fairey and Lefkovitch (1998) found that an available nitrogen supply within the range of 100-150kg/ha N was required to maximise seed yield. Phosphorous needs to be present within the system at 25ppm and potassium needs to be present at 150ppm (Anderson et al., 2014) for optimal seed yields. Sulphur needs to be applied at 50 kg/ha S annually when deficiencies are shown. When managing a tall fescue seed crop the post-harvest management practices also need to be considered as these have huge impacts on the seed yield the following season.

1.1 Breeding

Tall fescue is a species with a high degree of self-incompatibility (Silva and Goring, 2001). Self-incompatibility is a plant mechanism developed to prevent inbreeding and allow for improved genetic variation (Silva and Goring, 2001). This mechanism is controlled by multi allelic loci and results in complex interactions within the reproductive organs of the plant.

This is detrimental to the production of tall fescue cultivars as there is a lot of genetic variation. Because of this tall fescue cultivars can be considered as populations due to the genetic diversity within a sward. These populations must have a certain degree of uniformity morphologically to be considered a cultivar, but genetically there is a lot of variation. The most common technique used to create cultivars due to the self-incompatibility mechanisms is by ecotype selection. An ecotype is a naturalised population of a species with characteristics that have evolved with adaptations to suit the environment it is found in (Cohan, 2009). Ecotype selection involves selecting germplasm from these regions and testing for suitability as a forage species. Recurrent selection is used for phenotypic selection to refine these ecotypes to produce commercially available cultivars. The ecotypes used in tall fescue breeding are typically either of continental European or Mediterranean descent. Mediterranean cultivars of tall fescue are native to North Africa, the Middle East, Central Asia and Siberia. They typically have high cool season growth but are summer dormant (Innes, 2003; Volaire et al., 2009). These cultivars are typically more persistent due to growth ceasing over the hottest months. Continental cultivars of tall fescue are usually found in Europe and produce significantly more foliage from late spring to autumn than the Mediterranean types. There is a genetic barrier between Mediterranean and continental type tall fescue meaning they cannot be crossed, even though both ecotypes are hexaploid. The resulting progeny are often sterile or have meiotic irregularities (Hunt and Sleper, 1981). This makes progress in tall fescue breeding difficult to achieve.

1.2 Growth and Development

1.2.1 Tiller Initiation and Senescence

Perennial grass plants go through different life stages throughout their existence. Once germination occurs there are two distinctive development stages, the vegetative and reproductive stages (Huijser and Schmid, 2011). During the vegetative stage rapid growth occurs from tillering. Tillering is the production of lateral shoots by a plant of the *Poaceae* family (typically grasses). These tillers are made up of successive segments that can be defined as phytomers. A phytomer is the repeating unit made up of an apical meristem,

stem, leaves, nodes and latent buds (Thompson, 2014). During this phase tillers are actively growing until environmental cues trigger a response within the plant. Within the vegetative phase of growth the shoot apex cuts off new leaf primordia which are then unfolded and can be defined as foliage (Langer, 1979). This process occurs in an acropetal succession (developing in succession from base to apex). This period does not contain any stem extension, only tillering. The beginning of the tillering process begins with the production of a collar and cowl that encases the apex. This apex is then enclosed in a collection of developing leaves (Jewiss, 1972). During this period, deeper in the plant apex cell division occurs. This is the indication that tillering is going to occur. When leaf primordium overarch the apex the meristematic tissue develops into what is known as a bud (Jewiss, 1972). These buds then emerge from the leaf sheaths to form externally visible tillers. There is a direct correlation between the rate of tillering and light interception. Williamson et al. (2012) looked at the effect that light had on bud initiation for tiller formation. They found that a reduction in the Red to Far Red light ratio caused a 25% reduction in the number of buds that resulted in tillers in a variety of C₃ grasses. Williamson et al. (2012) also found that in C₃ grasses the addition of nitrogen had a significant effect on the number of buds that formed tillers. At a nitrogen concentration of 0 ppm only 40% of the buds formed tillers compared with 80% at a nitrogen concentration of 50 ppm.

Tiller production is highly important in determining final seed yield as there is a direct correlation between fertile tiller number and final seed yield (Heineck et al., 2020). This is because the more tillers available for vernalisation over winter, the more reproductive tillers that will produce seed heads (Hare, 1994). Fertile tiller number is dependent on a variety of environmental factors, as well as tiller senescence. Tillers need exposure to cold temperatures to be initiated for floral induction but for optimal tiller production that results in maximum seed yields milder winters are preferential. Hare (1994) reported that temperatures between 10°C to 15°C in early winter actually increased the number of tillers available for vernalisation whereas temperatures below this actually reduced tiller initiation, and therefore the number of fertile tillers producing seedheads.

Tiller generation and senescence works in a cyclic system. Tillers that do not go reproductive and develop seed heads are often the ones that end up dying off. These tillers were not

exposed to the required environmental cues mentioned above. This process is called tiller senescence. Tiller senescence is commonly a result of smaller vegetative tillers failing to compete for light. This causes an increase in the rate of leaf senescence as the senesced tillers then shade even more of the tillers. This usually occurs at a ceiling leaf area index (LAI). Leaf area index can be defined as the projected area of leaves over land (m²) (Waring and Running, 2007). The optimal leaf area index was defined by Bahmani (1999) as the point when even the lowest leaves in the canopy are able to meet their photosynthetic capabilities. Once a leaf area index of 95% is reached (95% light interception by canopy) the smaller tillers in the canopy are no longer able to access any light for interception and this causes senescence (Bahmani, 1999).

1.2.2 Juvenile Stage

The reproductive stage can be classified as the induction of flowers instead of tillers. For floral induction to occur environmental cues need to be met. These environmental cues are only beneficial for the plant at the later stages of the vegetative development phase (Huijser and Schmid, 2011). Before the reproductive phase can be reached the two vegetative growth stages need to have occurred. The first phase is called the juvenile phase. A juvenile stage is a vegetative stage of development where plants continue to increase in size, that needs to occur for plants to go reproductive. During this period plants are insensitive to environmental cues that would normally trigger floral initiation (Hare, 1992). The length of a juvenile phase is dependent on the species. In some grasses such as cocksfoot (*Dactylis glomerata*) and phalaris (*Phalaris aquatica*) the juvenile stage lasts a few weeks, comparative to bamboo (*Bambusa vulgaris*) that has a juvenile phase lasting a few months (Hare, 1992). Bean (1970) suggested that tall fescue plants have a juvenile stage that they need to pass through before vernalisation can occur, even if the cardinal vernal temperatures are met. Bean (1970) came to this conclusion after the discovery that 2-4-week-old seedlings required a longer period of vernalisation than 6-8-week-old seedlings. The trial involved growing plants in a heated glasshouse for either 0,2,4,6 or 8 weeks and then placing them in an unheated glasshouse for up to 23 weeks for a “vernalisation” treatment. Hare (1992) commented that in Bean’s trial there was no mentions of temperatures within these trials and suggested that vernalisation could have occurred in

the heated glasshouse if temperatures were to drop to 10°C (the maximum temperature for vernalisation in tall fescue (Hare, 1992)). Bean (1970) showed that the younger plants did have a longer vernalisation requirement than older plants, suggesting there is a short juvenile phase, but these results were not fully conclusive. This meant that the conclusion that a juvenile phase definitely exists in tall fescue could not be made. Hare (1992) also carried out a trial to determine whether a juvenile phase existed in tall fescue using the cultivar Grasslands Roa. The plants were established in a glasshouse with an average daily temperature of 21.3 °C from the 13th of June to the 1st of August. Plants from each treatment were sown at two weekly intervals to determine how differently aged plants responded to vernalisation. The plants were then transferred to vernalisation room for 0, 240, 480, 720 or 960 hours. The results showed that 64% of plants did not have a juvenile phase. The 36% of plants that did have a juvenile phase suggests that although a juvenile phase does exist in tall fescue, it varies significantly in genotypes, even within a cultivar.

1.2.3 Daylength

The vegetative stage of development in tall fescue ends once the required environmental cues that trigger the reproductive development phase have been identified. Tall fescue typically has an obligate short-day requirement, although this requirement varies between cultivars. This means that tall fescue has a requirement for a short-day photoperiod. Short day plants need to be exposed to less than 12 hours of light for an extended period of time. Bean (1970) found that for 90% of tall fescue plants to flower they needed to be exposed to 8-12 weeks of short days. When exposed to 0-4 weeks of short days between 0-20% of tillers went reproductive when exposed to the same temperatures. This short-day requirement is often co-dependent on temperature. A study by Templeton et al. (1961) looked at the effect that daylength had on floral induction in a glasshouse using different photoperiod lengths. The photoperiod length was either nine hours, or a lower intensity light from late afternoon until 10pm. The study found that the tall fescue plants did not necessarily require a short photoperiod. Under a 9-hour photoperiod length, 58% of plants still flowered. Comparative to this under the low intensity light treatment 100% of plants flowered. This suggests that a “short-day” treatment with lower intensity light is not an obligate requirement for all the plants within the cultivar. A short photoperiod is less

important for the signalling of floral induction when plants are exposed to temperatures required for vernalisation. When plants were grown without the presence of a cold period, the only plants to flower were the ones that were exposed to a short-day photoperiod. This suggests that there are multiple environmental factors that signal floral induction. The importance of the plant's exposure to these factors varies based on the individual plant. This is likely because tall fescue populations are very diverse due to the self-incompatibility mechanisms mentioned earlier. The exact length of the low intensity light treatment was not mentioned in this study, it only mentioned that the low intensity light treatment was applied in "late afternoon". Due to this factor the results of the study should be used as a reference but are not comparable to other studies. This study was able to show the requirement for multiple environmental factors for floral initiation to occur. This is contrary to the previous thought that vernalisation was the main controlling factor for floral induction.

1.2.4 Vernalisation

Tall fescue has a strong vernalisation requirement (Hare, 1992). Vernalisation is the acceleration of developmental stages by exposing plants to cool temperatures (Sadras and Calderini, 2009). Plants enter the inductive stage where they can respond to cold temperatures. For tall fescue temperatures below 10°C allow for vernalisation to occur within the plant. Any temperatures above 0°C allows effective vernalisation (Hare, 1992). In tall fescue each tiller must be exposed to temperatures below 10°C separately. This is a result of the vernalised state not being translocated around the plant (Hare, 1992). Hare (1992) showed that after 960 hours (40 days) of vernalisation, 64% of plants within the population were vernalised. A vernalisation period of 1440 hours (60 days) was required for 100% of the plants to go reproductive. There is limited research on the length of vernalisation required for tall fescue plants to go reproductive. This is in part likely due to the genetic variability between and within cultivars making it difficult to use a blanket recommendation. Without a vernalisation period only 4% of the tall fescue tillers will get to a reproductive growth stage (Hare, 1992).

1.2.5 Carbohydrate Reserves

Non-structural carbohydrates are required for maintenance and growth of plants. These assimilate carbohydrate stem reserves are produced as a result of photosynthesis (Jones, 2013). Grass plants can utilize the sun's energy only during daylight. When the leaves produce more carbohydrate than is needed for growth and maintenance, some of the production can be translocated to the storage organs. When production is insufficient to meet the demands of the plant, the stored carbohydrates are called on for continued growth. This situation causes no problem unless the stored carbohydrates are depleted. Non-structural carbohydrates are glucose, fructose, sucrose and fructose polymers which make the carbohydrate source or sink in the plant (Jones, 2013). When plants have insufficient assimilatory reserves for growth these carbohydrate reserves are depleted. This is due to growth in the plant prioritising growth over carbohydrate storage (Jones, 2013). After a defoliation event in grasses, fructose reserves in the stem are rapidly depleted (Sullivan and Sprague, 1943). This decline is because of the rate of photosynthesis is insufficient to meet demands. The return to original carbohydrate levels typically stabilises 4-5 weeks after defoliation, although this is can be dependent on environmental temperatures (Davies, 1965). Carbohydrate storage increases when leaf growth rate slows, and leaf area is large. This was reinforced by Volenec (1986) who showed a 50% decline in stem carbohydrate reserves 4 days after a defoliation event. After 24 days total non-structural carbohydrates within the stem reach 93% of their initial levels. This suggests that under a system such as a set stocked system, if leaf area is not able to recover and grow to its initial size, carbohydrate reserves will decline.

1.3 Components of Seed Yield

Seed yield components are the different elements of the plant that contribute to overall seed yield. The key seed yield components in tall fescue are number of fertile tillers, spikelets per fertile tiller, florets per spikelet, number of seeds per spikelet, and seed weight. Wang et al. (2011) developed a model to determine whether there was a relationship between each component and the final seed yield. It was determined that each

of the seed yield components had a strong correlation with the final yield and can be used to predict final yield. The component that had the greatest correlation with final seed yield was spikelets per fertile tiller ($R^2 = 0.98$), suggesting this is what should be focussed on in future breeding programs when trying to improve seed yield.

The model developed is as follows:

$$Z = -106.49 + 0.24 \cdot Y_1^{0.42} \cdot Y_2^{0.98} \cdot Y_3^{0.89} \cdot Y_4^{0.07} \cdot Y_5^{0.59}.$$

Where:

Y_1 = number of fertile tillers

Y_2 = spikelets per fertile tiller

Y_3 = florets per spikelet

Y_4 = number of seeds per spikelet

Y_5 = seed weight

Z = overall seed yield

1.3.1 Establishment

There are a variety of components that affect the components of seed yield. These components can be environmental and agronomic. One factor affecting this is the establishment phase. A study by Hare et al. (1988) looked at the effects that different sowing dates had on autumn sown prairie grass (*Bromus willdenowii*). The three sowing dates were the 11th of March, and 1st and 22nd of April. Fertile tiller number declined from 490 to 360 tillers/m² when sowing date was delayed to 22nd April. Spikelets per head also declined from 37 to 28 spikelets per head when sowing date was delayed from the 11th of March to the 22nd of April. When sowing date was delayed by the six weeks there was also a 50% decline in seed yield. Hare et al. (1988) showed that late sown prairie grass will never have the tillering capacity of earlier sown plants due to the thermal time requirement for tillers to be produced. The lower tiller numbers were a result of low temperatures. This

reduces seedling vigour resulting in slower establishment and therefore tiller development (Hare, 1998).

A study by Fairey and Lefkovitch (1999) looked at another factor affecting successful establishment which is plant density in tall fescue. Plant density can be altered through the sowing rate of the crop. Fairey and Lefkovitch (1999) reported a row spacing of 20 cm with a density of 100 plants per m² gave a seed yield of 1085 kg/ha in the first harvest year after sowing. However, a spacing of 40cm rows with a lower plant density of only 50 plants per m² produced a higher seed yield of 1824 kg/ha. This is likely due to wider row spacing allowing more light into the canopy. This in turn allows for a higher rate of light interception which improves photosynthetic rate. This creates a higher rate of canopy development and more tillers produced. And as the model above mentions there is a direct correlation between the number of fertile tillers and the final seed yield. At a row spacing of 80 cm the plant population was 25 plants per m² and the seed yield declined to 1183 kg/ha. This is likely due to the wider row spacing not allowing for the development of a complete canopy, therefore light interception was inefficient (Fairey and Lefkovitch, 1999).

Sowing method is another factor that is influential on the components of seed yield. Charles et al. (1991) looked at the effects that using four different sowing methods had on the final seed yield of a tall fescue crop. The first sowing method was an inverted triple disc method, carried out by a Duncan 730 multiseeder triple disc direct drill. The second method was using an Aitchison Seedmatic 1000 inverted T drill. The third method was cultivating a seedbed, rotary hoeing twice up to 100 mm and sowing with a triple disc. The last treatment was an aerial sowing method also known as broadcasting. At 25 days after sowing the inverted T and the triple disc resulted in 72 and 62 plants per m² respectively. These methods were not significantly different from each other. The cultivation method produced 26 plants per m². The Aerial sowing method produced the lowest number of plants at only 5 per m². This is likely due to discing methods obtaining a fine firm seedbed. Comparatively broadcasted seeds must penetrate the soil surface that has not necessarily been cultivated.

1.3.2 Grazing

Grazing is an agronomic practice that can alter the components relating to final seed yield. Grazing is only used to manage residue in seed crop systems where stock is readily available. Stock usually graze seed crops following harvest and into the winter until closing. Santillano-Cázares et al. (2008) in Oklahoma looked at the effect that grazing had on different components of seed yield in tall fescue. In the first year of seed production there was 151 seed heads per m² in plots that had been grazed compared with 83 seed heads per m² in the non-grazed plots. This is likely due to defoliation increasing the available light for interception by the plant (Santillano-Cázares et al., 2008) during the tiller initiation growth stages. The number of seeds per m² was 1684 seeds per m² lower in the ungrazed trial than in the grazed trial. These differences were significant although could have been so extreme due to the ungrazed trial not having any defoliation management and just being left to grow unchecked. Future research could look at the effects that mowing for hay or silaging has in contrast to grazing. Seeds per seed head and seed weight (mg/seed) were not significantly different between both grazing treatments.

1.3.3 Plant Growth Regulators

Plant growth regulators are phytohormones that play a significant role in growth and development of plants (Patel et al., 2019). Synthetic plant growth regulators can be applied to crops to mimic and exaggerate effects of natural hormones. When applied at low concentrations plant growth regulators (PGR) can affect cell division, cell expansion, cell structure and function (Small and Degenhardt, 2018). In agriculture they are typically used to influence plant height to prevent lodging. Trinexapac-ethyl (TE) is a PGR that blocks the synthesis of gibberellic acid and reduces growth (Rolston et al., 2004). Rolston et al. (2004) carried out six trials looking at the effects that TE had on tall fescue. At an application rate of 200 g TE/ha the seed yield increase was 67%. At an application rate of 300 g TE/ha there was an increase of 72% in seed yield compared to the control treatments where no PGR were applied. These increases in seed yield are based on a variety of factors. One of these is the prevention of lodging. Lodging occurs due to bending of the culm at the basal stem internodes (Dai et al., 2017). Anderson et al. (2016) found that 93% of tall fescue plants lodged without the addition of PGR. Lodging reduced seed yield by as much as 31% when compared to a crop that was artificially supported in an upright position (Anderson et al.,

2016). This decrease is due to difficulties harvesting the seed, causing a greater harvest loss. Anderson et al. (2016) found that seed numbers increased by 19675 seeds/ m² when Trinexapac-ethyl (TE) plant growth regulator was applied. Harvest index was also 1.7% higher in plots treated with TE. Cycocel (CCC) is another PGR used on tall fescue seed crops. In the same study CCC reduced lodging by 23.3%. This showed that CCC can reduce lodging but is not as effective as TE in tall fescue seed crops. The same trend was also reflected in the seed number m². The crop had an additional 6308 seeds m² when treated with CCC compared with the control. This suggests that CCC and TE are both beneficial to increasing the components of seed yield. TE is more effective than CCC overall.

1.3.4 Irrigation

Irrigation is another factor that has a significant impact on the components of seed yield. A study by Martiniello (1998) looked at rainfed, irrigated up until June and full irrigation systems in a variety of pastoral species in a Mediterranean environment. Tall fescue seeds per stem were not significantly different under irrigation or rainfed. This is likely due to tall fescue being a drought tolerant species. Seed weight was also not significantly different for rainfed or irrigated conditions. Tall fescue was not negatively affected when not under irrigation as the cultivar used is one that is summer dormant. Therefore during the periods of drought and heat stress the plant would not be growing (Martiniello, 1998).

Mediterranean tall fescue produces most of its biomass during the spring period when there is enough moisture resulting in irrigation having little to no effect on seeds per stem and seed weight. Stem density was significantly higher under irrigation at 515 stems per m² compared with 374 stems per m² under rainfed conditions. Seed yield was significantly higher under irrigated conditions at 300 kg/ha compared with 158 kg/ha under rainfed conditions. The irrigation until June treatment was not significantly different to the rainfed conditions. There was a direct correlation between stem density and seed yield ($R^2 = 0.86$). The irrigation treatment increased seed yield as additional water during early spring when tillers are being produced allowed for a higher number of tillers to be produced.

1.3.5 Nitrogen

Nitrogen is the fourth most abundant element in cells. It is one of the major limiting factors for growth and development in all plants (Hirel and Krapp, 2020). Nitrogen availability is a key factor affecting plant reproduction (Canto et al., 2020). A study by Fairey and Lefkovitch (1998) looked at the effect that nitrogen fertiliser had on tall fescue seed yield. They found that there were no significant differences in seed yield at application rates of 50 kg/ha to 150 kg/ha (1132 and 1197 kg/seed respectively). Fairey and Lefkovitch (1998) found no significant differences in seed yield between fertiliser application timings in September or October. The trial has already had an application of 7 kg N/ha suggesting that there was enough nitrogen in the system that the additional timings did not affect seed yields.

1.4 Post-Harvest Residue Management

New Zealand's herbage seed industry is well known for producing perennial seed crops. Perennial seed crops require different management practices than annual seed crops due to the residue leftover on the paddock post-harvest. This residue or "trash" as it is sometimes referred to needs to be removed from the system to allow the crop underneath to recover and produce seed for the following year. This makes perennial seed crops more difficult to grow but does have an economic benefit. Because the paddock does not have to be resown the following year. Post-harvest management of perennial seed crops is important as the reproductive tillers are formed in the autumn and early winter (Hare, 1993). This tiller formation can seriously be inhibited when the residue is not managed correctly which will reduce overall yields (Hare, 1993). Perennial seed crop management differs based on location, climate and species.

1.4.1 Thermal Management

Thermal residue management is the process of burning the remaining residue from the seed crop. It is a practice that has in recent times declined in popularity due to adverse environmental effects (Steiner et al., 2006). Burning is a beneficial practice as it opens the

stand, allowing light into the crown of the plant. There is a direct correlation between the availability of light to the crown of the plant and tiller initiation (Hare, 1998). This allows the production of earlier developing new tillers that will go reproductive. These earlier produced tillers are also shorter and more prostrate, therefore reduce shading within the stand (Hare, 1993, 1998). These tillers have higher radiation use efficiency, as they have more effective photosynthetic tissues for capture of light (Hare, 1998). The timing of burning is highly influential in how effective the treatment is, as burning too late will reduce yields due to stand injury (Canode, 1972). Chilcote and Youngberg (1975) looked at the effects of burning residue using propane early and late in the season. Chewing's fescue (*Festuca rubra*), perennial ryegrass (*Lolium perenne*) and Merion bluegrass (*Poa pratensis*) all showed significantly lowered yields when burning was carried out later in the season. This is likely due to more green material being present within the sward that would suffer from injury resulting in less tillers produced (Chilcote and Youngberg, 1975). Cocksfoot (*Dactylis glomerata*) was the only species that did show significantly different results with early or late burning. This is likely due to cocksfoot's slow growth during the winter period (Barker et al., 1985), which results in less green material present when late burning occurs that would suffer from injury

In the USA two types of thermal management methods were commonly used, open field burning and propane burning. Propane burning has the same advantages as open field burning without the emissions or risks Young et al. (1998). Propane burning is a relatively expensive technique and needs to be carried out once significant portions of stubble are removed through mowing or chopping (Chilcote and Youngberg, 1975). Young et al. (1998) looked at the effect of these two thermal methods of residue management. This study compared the thermal practices mentioned above with non-thermal close clip treatments. Overall panicles per unit area (m^2) were not significantly different between the open-burn and propane-burn treatments. The thermal treatments did produce significantly more panicles per unit area than the nonthermal method, which produced around 50% less panicles per unit area. There were no significant differences between the number of seeds per panicle or the individual seed weight.

1.4.2 Clean Non-thermal Management

Clean non-thermal practices are also used as a management practice to control post-harvest residue. These practices remove around 75% of the straw load (Chastain et al., 1997).

Mechanical clean non-thermal removal is the process where a crop is windrowed, then harvested by the combine. Straw is then raked and baled (Hart et al., 2012). This straw can then be sold as stock feed. In Oregon, up to 1.1 million tonnes of grass straw needs to be managed with significant reductions in open field burning (Hart et al., 2012). Grass straw is in some cases considered a low-quality feed but when used through supplementary feeding it can be highly beneficial in agricultural systems. This straw offers an additional income to the grower so has become a more attractive option over burning (Hart et al., 2012). Baling often produces similar or higher yields to when straw is chopped and left on the paddock (Chastain et al., 1997; Hart et al., 2012), as well as providing the economic incentive. Hart et al. (2012) compared the relative seed yield of non-chop with chop treatments and showed significantly lower relative yields compared to bale treatments. A relative yield index is typically used as seed yields vary significantly annually so a direct yield comparison would not necessarily reflect the effectiveness of the bale treatment compared to the chop treatment.

Grazing is an effective tool to manage residue in farm systems that have livestock.

New Zealand often uses stock to control residue left behind (Hare, 1993). This is a less popular strategy globally due to lack of stock availability for grazing at critical periods (Hare, 1993). Sheep are often able to graze much lower into stands than close cutting (Hare, 1998). Issues arise when stands age and become too dense for sheep to penetrate. Grazing can be just as effective as open field burn treatments commonly used in Oregon as evident in a study by Holman et al. (2007). There were no significant differences in Kentucky bluegrass (*Poa pratensis*) seed yield between baling early then grazing with a low stocking rate, grazing with a high stocking rate or thermal treatments. Similar results were found in a study by Hare (1993) who found seed yields were not significantly different between cutting or grazing treatments.

Vacuum sweeping after harvest is another effective residue management tool. This method involves the baling and removal of straw and is then followed by close cutting (down to 1-2cm above soil surface and removal of stubble (Young et al., 1994). Young et al. (1994) compared bale only, vacuum sweep and open field burning treatments. The vacuum sweep treatments produced the highest seed yields at 1834 kg/ha. This was likely a result of having very low residue residuals. Reducing the residue allows for light to reach the growing point and causes the induction of earlier developing tillers that will go reproductive (Hare, 1998). It was unexpected that burning produced the lowest average seed yields at 1588 kg/ha as it typically is assumed to produce the highest seed yields. This could potentially be because only one site was sampled for the burn treatment compared to between 4-6 sites being sampled for the bale + vacuum sweep treatment and the bale only treatments. The bale treatment did not produce significantly different seed yields (1530 kg/ha) compared to the open burn treatment. This suggests that in some cases baling and removal of straw can be just as effective as burning.

1.4.3 Management with Full Straw Load Retained

Sometimes growers choose to chop the residue with full straw load retained on the pasture. With this management strategy the straw is left to decompose in the field (Hart et al., 2012). For this treatment to be effective straw length can be reduced by the process of chopping the straw finer. This process is beneficial as it allows for nutrient cycling (Hart et al., 2012). Uniform spreading of the finely cut straw is paramount so that it settles within the rows and can decompose. Flail chop treatments in some cases have lower yields than straw removal treatments (Hart et al., 2012; Young et al., 1999) in species such as tall fescue and perennial ryegrass. Often this is due to the shading effect that occurs when straw is not chopped finely enough to settle between the rows and decompose. Similar results were found by Chastain et al. (1997) in Kentucky bluegrass with over a 10% decrease in yield when using a flail chop treatment. The value in this treatment and the reasoning why this practice is used in some areas is due to the nutrient values of the straw. Perennial ryegrass contains on average 1% nitrogen (N), 0.1% phosphorous (P), 2% potassium (K), 0.35% calcium (Ca), and 0.12% Magnesium (Mg). Tall fescue has similar nutrient contents with

slightly higher Mg at 0.18%. When this straw is removed the nutrient content removed within the straw needs to be replaced.

1.4.4 Residue Management in Tall fescue

Tall fescue as a perennial grass species produces most of the tillers that will go reproductive during the autumn. This is due to the strong vernalization requirement of the crop (Hare, 1992). Only 4% of tall fescue tillers that are not vernalized will go reproductive (Hare, 1992). Young et al. (1999) looked at the effect of flail chopping, propane burning or open field burning on tall fescue seed yield components. There were no significant differences between propane and open field burning treatments. This suggests that in areas with open field burning restrictions, propane burning may be a solution. Propane burning also has the added advantage of being more environmentally friendly as there is lower emissions of pollutants than with open field burning (Young et al., 1999). Flail chop treatments produced 207 kg/ha less seed than the open burn treatment. This is not surprising in a species such as tall fescue because of the dense growth habits and large quantities of biomass (Hare, 1992). The amount of residue returned to the crop was not mentioned suggesting that it may not have been chopped finely enough, shading the growing points (Hare, 1992). Hare (1992) also showed the main factor that determines final seed yield was the amount of light that was able to access the crown of the plant. The variations of red and far-red light affect the tiller dynamics drastically, which will in turn affect the overall seed yield (Casal et al., 1987; Young et al., 1999). Therefore, as tall fescue is a very densely tillered plant, residue removal treatments will produce higher yields than residue returned when residue is not chopped finely enough. Fairey and Lefkovitch (2001) looked at burn timings on crops. A single burn treatment produced seed yields of 180 mg/panicle. The double burn treatment produced significantly lower seed yields at 160 mg/panicle. This was likely due to the second burn being carried out too late in the season, which caused senescence of new developing tillers (Canode, 1972).

1.4.5 Summary

To conclude grass seed crops are very complex to manage as there are so many factors that influence the seed yield components. A knowledge of plant physiology is highly important when deciding what agronomic practices to use. Tall fescue is a highly complex species due to self-incompatibility mechanisms which result in highly diverse populations. These populations are sold as cultivars but are not genetically identical. There is significant variation between cultivars based on where germplasm originates. Continental germplasm typically requires vernalisation, but Mediterranean cultivars do not have that obligate requirement. Evidence for a juvenile stage is inconclusive with some cultivars demonstrating this but others not. The components of seed yield and how they are managed have a direct correlation with seed yield. Factors such as number of fertile tillers, spikelets per tiller and florets per spikelet have the greatest correlations with yield. Agronomic practices at establishment such as sowing date and sowing method influence how the crop will develop and this will influence any future practices. Grazing, plant growth regulators, fertiliser and irrigation all influence the seed yield, but the extent of the impact varies between species and cultivars. Post-harvest residue management treatment applied to cool season perennial grass crops is highly influential on the final seed yield harvested. Open field burning has become highly regulated, due to emissions and safety concerns suggesting that although this method provides good seed yields, it is not a viable option in some places. Propane burning in some studies is proving just as beneficial in removing residue as open-field burning, reflecting the potential for this to become an attractive alternative to open field burning for growers. Clean non-thermal practices such as baling have the benefit of an additional income from the straw. Grazing works well to remove residue, but stocking rates need to be carefully managed to prevent the crop from getting too long and going “rank”. Full straw load treatments often result in lowered seed yields due to shading occurring at the growing point of the plant. These can be mitigated to an extent with chopping straw finely into a chaff so that it settles within the rows. Retaining a full straw load also recycles nutrients back into the soil that would otherwise need replacing as fertiliser, therefore reducing the costs of inputs. Overall no one management practice is better than others as they all provide different benefits.

1.4.6 Primary Objective

The primary objective of this research was to quantify components of seed yield for tall fescue and relate this to the management of post-harvest residue, vegetative growth and closing date. The aim of this project was to be able to refine knowledge on commonly used non-thermal post-harvest management practices in Tall fescue seed crops so that management recommendations can be made to farmers.

Chapter 2

Materials and Methods

2.1 Site

The experiment was conducted at Barrhill, Methven in paddock 10 (-43.711960384568506, 171.89898549803297) (Figure 1.), on Simon Lochhead's Farm. The tall fescue paddock was sown in March 2018 and was in its third year of production. The trial began on the 23rd of January 2020 and seed was harvested on the 12th of January 2021. The soil is a deep, well drained, immature pallic silt loam.



Figure 1. Trial site at Barrhill, Methven.

2.2 Tall Fescue Cultivar

The experiment was conducted on a crop of tall fescue (*Festuca arundinacea*) cv. Volupta, a perennial French cultivar typically used for forage in Europe. It is grown in New Zealand as a multiplication seed crop for export back to Europe. Volupta is an intense green hexaploid cultivar. It has long to very long leaves during the vegetative growth phase. It is an early to medium heading variety once reproductive initiation has been achieved. It has medium to long reproductive stems and inflorescences. Volupta is a cool season cultivar with excellent winter growth and dry matter production with maximum yield of up to 14,500 t DM/ha (France, 2014).

2.3 Experimental Design and Treatments

Two trials were conducted at the site alongside each other (Figure 2.) using a split plot design. Each treatments had four replicates, that were arranged in a randomized complete block design. Trial 1 was a grazing exclusion trial that involved different mowing frequencies (Figure 3). The whole plots (12x25 m) were fenced using flexinet to keep stock out. The main

plots were two post-harvest residual heights, either; *i*) conventional, the crop stubble left at the harvest mowing height of 14 cm, or *ii*) mown, stubble cut post-harvest using a disc mower to 7 cm. Sub plots (12 x 4 m) consisted of three mowing frequency managements; *i*) nil, *ii*) lax, where plots were cut once at the end of May, and *iii*) frequently, where plots were mowed monthly (Table 1.). The mowing frequency treatments were cut to the height of the main plots. The cut residue was retained on all of the plots.

Table 1. Treatment plan for Trial 1, the grazing exclusion trial. Whole plots are 12 x 25 m.

Trial 1.	Plots		Sub-Plots	
Plot Size	12 x 25 m		12 x 4 m	
Treatments	(i)	Mown to 7 cm	(i)	Nil Mowing
	(ii)	Mown to 14 cm	(iii)	Lax Mowing
			(iv)	Frequent Mowing

Trial 2 was a grazing inclusion trial that involved using stock to manage the residue (Figure 4.). The stock used were calves and store lambs that were set stocked from seed harvest until closing (mid-June). Within this trial an additional nitrogen fertiliser application trial was also included. This consisted of additional N at an *i*) early timing during August *ii*) standard practice timing during September or *iii*) late timing during October (Table 2.). The application rate for the additional nitrogen was 50 kg N ha⁻¹.

Table 2. Treatment plan for Trial 2, the grazing inclusion trial. Whole plots are 12 x 25 m.

Trial 2.	Plots		Sub-Plots	
Plot Size	12 x 25 m		12 x 4 m	
Treatments	(i)	Mown to 7 cm	(i)	Early N Fertiliser Application
	(ii)	Mown to 14 cm	(ii)	Standard Practice N Fertiliser Application
			(iii)	Late N Fertiliser Application

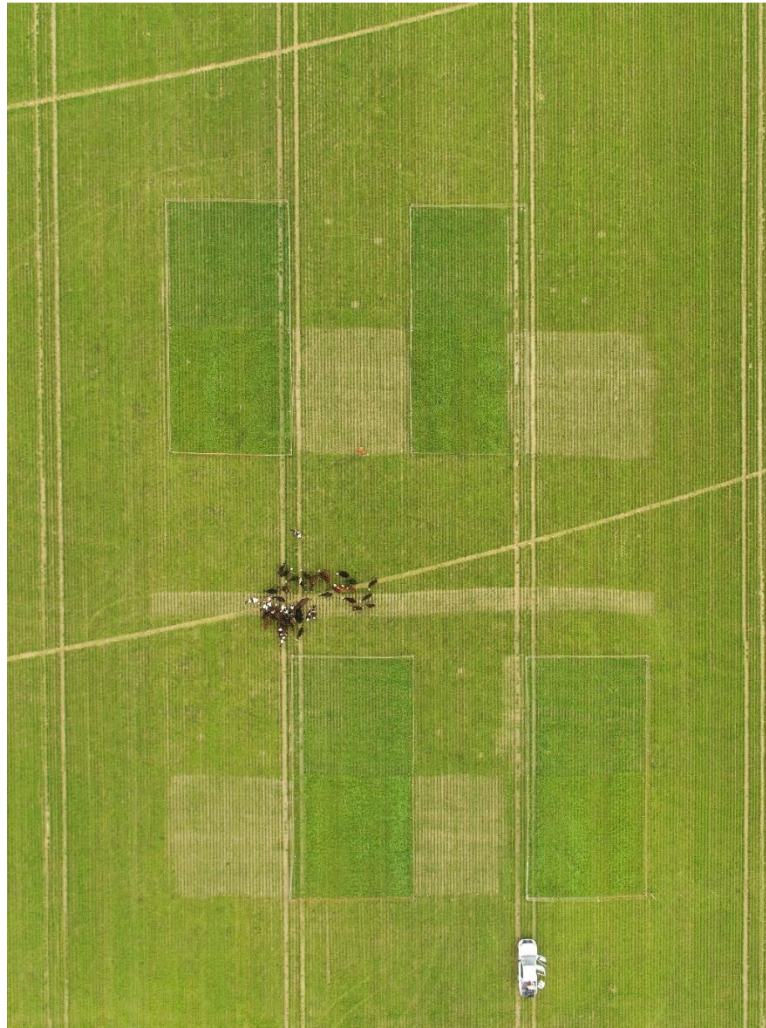


Figure 2. Drone image captured by Richard Sim, overlooking trial 1 and 2. Trial 1 had the plots with flexinet fencing surrounding them. The plots for Trial 2 were not fenced so that the stock could get access to them for grazing.

P	High	Cut	Freq		Grazed Trial	p	High	Cut	Lax		Grazed Trial
l	High	Cut	Lax			l	High	Cut	Freq		
0	High	Cut	Nil			o	High	Cut	Nil		
t	Low	Cut	Lax			t	Low	Cut	Freq		
	Low	Cut	Nil				Low	Cut	Lax		
1	Low	Cut	Freq			3	Low	Cut	Nil		

Pivot Wheel Track

	Grazed Trial	P	High	Cut	Nil		Grazed Trial	P	High	Cut	Nil
		l	High	Cut	Freq			l	High	Cut	Lax
		0	High	Cut	Lax			0	High	Cut	Freq
		t	Low	Cut	Nil			t	Low	Cut	Freq
			Low	Cut	Lax				Low	Cut	Nil
		6	Low	Cut	Freq			8	Low	Cut	Lax

Back Track Road

Figure 3. Trial Plan for Trial 1. High = stubble left at 14 cm; Low = stubble cut to 7 cm; Nil = no subsequent mowing; Lax = cut to the height of original high/ low treatment at closing; Freq = cut to the height of original high/ low treatment monthly until closing.

	Ungrazed Trial	p	Low	Grazed	Early		Ungrazed Trial	p	Low	Grazed	Std
		l	Low	Grazed	Late			l	Low	Grazed	Early
		o	Low	Grazed	Std			o	Low	Grazed	Late
		t	High	Grazed	Std			t	High	Grazed	Early
			High	Grazed	Early				High	Grazed	Std
		2	High	Grazed	Late			4	High	Grazed	Late

Pivot Wheel Track

P	Low	Grazed	Late		Ungrazed Trial	P	Low	Grazed	Late		Ungrazed Trial
l	Low	Grazed	Std			l	Low	Grazed	Early		
0	Low	Grazed	Early			0	Low	Grazed	Std		
t	High	Grazed	Early			t	High	Grazed	Late		
	High	Grazed	Late				High	Grazed	Std		
5	High	Grazed	Std			7	High	Grazed	Early		

Back Track Road

Figure 4. Trial Plan for Trial 2. High = stubble left at 14 cm; Low = stubble cut to 7 cm; Nil = no subsequent mowing; Early = Additional nitrogen fertiliser application of 50 kg/ha in August; Std = Additional nitrogen fertiliser application of 50 kg/ha in September; Late = additional nitrogen fertiliser application of 50 kg/ha in October.

2.4 Paddock Management Prior to Trial

The paddock was in its third year of seed production. It was sown in spring 2018 at 30 kg/ha into 30 cm rows. In the autumn prior to this trial the paddock had received 312 kg/ha of a

base mix fertiliser including, 31 kg/ha nitrogen, 22 kg/ha phosphorous, 15 kg/ha potassium, 7.9 kg/ha magnesium, 19 kg/ha calcium and 30 kg/ha sulphur.

2.5 Herbicide and Plant Growth Regulators (PGR)

Herbicides and PGRs were applied as standard practice alongside the rest of the paddock. The herbicide Atraflo (a.i. Atrazine 500g/l) was applied at 600ml/ha. Mixed in with this was Karmex (a.i. Diuron: 3-(3,4-dichlorophenyl)-1,1-dimethylurea (80%)) applied at an application rate of 1.25kg/ha. This combination was applied on the 22nd of May to remove and prevent the growth of any volunteers from the sward. The paddock received a PGR application of 1.5 l/ha Cycocel (a.i. 750 g/l chlormequat-chloride) and 1.2 l/ha Moddus Evo (250 g/l trinexepac ethyl) on the 3rd of October.

2.6 Climate Data Monitoring

Temperature and humidity were constantly recorded throughout the trial using a HOBO MX2301A datalogger weather station with a MX2300 Large Solar Radiation shield (Figure 5.). Measurements were taken hourly from the beginning of the trial until seed harvest.



Figure 5. HOBO MX2301A datalogger weather station with a MX2300 Large Solar Radiation shield out in the field.

2.7 Irrigation

The trials were under standard practice irrigation with the rest of the paddock under a centre pivot irrigation system as part of a crop rotation. The crop was irrigated so that it did not exceed the critical soil moisture deficit of 120mm (soil depth of 400mm, root depth of 60mm) (Table 3.).

Table 3. Monthly rainfall, evapotranspiration (ET), irrigation and soil moisture deficit (SMD) of the site over the growing season.

Month	Rainfall (mm)	ET (mm)	Irrigation (mm)	SMD (mm)
January	2.0	38.9	50	28.9
February	48.6	106.2	50	36.5
March	16.4	71.4	0	91.5
April	27.8	51.5	0	115.2
May	33.8	31.5	0	112.9
June	114.6	14.6	0	12.9
July	15.6	18.3	0	15.6
August	47.4	38.5	0	6.7
September	77.4	79	0	8.3
October	65.4	90.8	25	8.7
November	109.2	105	45	0
December	50.8	126.8	20	15.5
January	52.4	36.5	0	0

2.8 Nutrient Levels and Fertiliser Applications

To ensure that nutrients were not a limiting factor for seed yield in this trial, foliage and soil samples were taken and analysed by Hill Laboratories in Hornby. The soil samples were taken using a soil corer to a depth of 150 mm, on the 5th of February 2020 to assess spring fertiliser application requirements. Soil samples had a basic soil test (includes pH, Olsen Phosphorus, Calcium, Magnesium, Potassium, Sodium, Cation Exchange Capacity, Base Saturation, Volume Weight), Sulphate-sulphur test, organic matter test, Ammonium-N test

and Nitrate N. The results showed that most of the nutrients were at adequate levels (Table 4.). The Olsen P was slightly low at 13 mg/L, but not concerning so maintenance fertiliser applications were enough to bring this up. The potentially available nitrogen was also low at 86 kg/ha.

Table 4. Soil test results from soil cores taken on the 5th of February 2020 from a depth of 150mm.

Soil Test to 150 mm Depth			
Analysis	Units	Level Found	Medium Range
pH	pH	6.3	5.0-7.2
Olsen P	mg/L	13.0	8.0-20.0
Potassium	me/100 g	0.4	0.3-1.0
Calcium	me/100 g	6.9	4.0-14.0
Magnesium	me/100 g	0.3	0.5-2.0
Sodium	me/100 g	0.1	0-0.5
Sulphate Sulphur	mg/kg	7.0	20.0-50.0
Potentially Available N	kg/ha	86.0	150.0-250.0
Anaerobically Mineralizable N	mg/g	56.0	-

On the 14th of August soil samples were taken using a soil corer to a depth of 0-300 mm and 300-600 mm. These were taken from each of the plots but as there were no significant differences among of the treatments they were averaged. The samples taken at the depth from 0-300 mm were analysed at Hill Laboratories for sulphate sulphur, ammonium-N, nitrate-N and mineral-N (combination of ammonium-N and nitrate-N). The results showed that sulphate sulphur was in the moderate range (Table 5.). The mineral N tests showed lower nitrogen levels than was expected. The soil cores taken at a depth of 600 mm were only analysed for ammonium-N, nitrate-N and mineral-N. The results showed slightly lower nitrogen levels (Table 6.) than expected and therefore additional spring nitrogen fertiliser was required.

Table 5. Soil test results from soil cores taken on the 14th of August 2020 from a depth of 300mm.

Soil test to 300 mm Depth

Analysis	Units	Level Found	Medium Range
Sulphate Sulphur	mg/kg	13.4	10.0-20.0
Ammonium-N	mg/kg	2.4	-
Nitrate-N	mg/kg	1.4	-
Mineral-N	mg/kg	3.8	-

Table 6. Deep N Soil test results from soil cores taken on the 14th of August 2020 from a depth of 600mm

Soil Test to 600 mm

Analysis	Units	Level Found
Ammonium-N	mg/kg	1
Nitrate-N	mg/kg	< 1
Mineral-N	mg/kg	1

Foliage tests were also carried out on February the 11th to help assist with decision making around fertiliser application. The foliage was collected at random across the trial site and combined as most of the treatments had not been implemented. Each sample contained 500 g of herbage. This was then submitted to Hill Laboratories for analysis. The results showed that most of the nutrients were within the acceptable range (Table 7.).

Phosphorous was below the medium range and therefore spring phosphorous fertiliser was required.

Table 7. Foliage test results sampled on the 02/11/2020.

Foliage Test

Analysis	Units	Level Found	Medium Range
Nitrogen	%	2.9	2.5-4.5
Phosphorous	%	0.22	0.35-0.5
Potassium	%	3.1	2.0-4.0
Sulphur	%	0.37	0.28-0.36
Calcium	%	0.6	0.40-0.50

Magnesium	%	0.27	0.16-0.22
Sodium	%	0.07	0.05-0.15
Iron	mg/kg	310	50.0-80.0
Manganese	mg/kg	123	30.0-80.0
Zinc	mg/kg	14	20.0-40.0
Copper	mg/kg	5	6.0-9.0
Boron	mg/kg	11	3.0-7.0

The fertiliser applications to this trial were decided based on the nutrient testing (Table 8.).

Table 8. Autumn nutrient applications of fertiliser for both trials.

Date	Product	Rate (kg/ha)	Applied Nutrients					
			N	P	K	S	Mg	Ca
18/02/2020	Topsoil Base Mix	340	9	18		41	32	24
16/03/2020	Sustain N	70	32					
	Sulphate of Ammonia	70	14			15		
30/03/2020	Urea	100	46					
04/04/2020	Urea	100	46					
	Yara Vera AMIDAS	125	50			7		
	Total		197	18	0	63	32	24

2.9 Sampling/Measurements Prior to Seed Harvest

2.9.1 Quadrat Cuts

Quadrat cuts were taken on the 20th January after the initial seed harvest to assess the biomass remaining as well as the residue returned to the field for each of the sub-sub plots. These were taken from a 0.5 m² quadrat using a sickle. The grass was cut to ground level. In the laboratory the total sample was separated into green material and dead matter. These

fractions were weighed and then oven dried separately at 90 °C for 48 hours to determine the dry weight. Quadrat cuts were taken again on the 18th of February, the 6th of May, and then once again just before seed harvest on the 28th of December. The aim of taking the quadrat cuts was to assess the biomass over the winter period and then prior to harvest for harvest index calculations.

2.9.2 Tiller Counts and Sizing

Tiller counts were taken from each of the sub-sub plots in both trials. Each tiller count involved using a shovel to dig out a 10 x 20 cm wedge out of the drill row. The wedge was transported back to the laboratory and then the tillers were removed from the soil using a scalpel at ground level. The total number of tillers was then counted from each sample and weighed. A sub-sample of 50 tillers picked at random was measured for width using a specific tiller sizing tool (Figure 6.) and these were separated into six size categories. These categories were based on the size of the tiller 5 mm from the base. The tiller was slid down the v-shaped tool until it could not go any further. The measurement was recorded from where the tiller stopped, without additional pressure to push it further. The tiller sizing tool was calibrated using electronic callipers. The total sample was then oven dried at 90°C for 48 hours to determine dry weight. Tiller counts were taken on the 6th of July, the 16th of November and the 24th of December. The aim of carrying out tiller counts was to assess the number of vegetative tillers that could potentially produce a reproductive seed head and to see if tiller size during the vegetative growth phase influenced final seed yield.



Figure 6. Tiller Sizing tool created by Simon Foley, designed by Murray Kelly

2.9.3 Light Interception Readings

Light interception readings were carried out periodically until canopy closure to determine the light reaching the crown of the plant. This was done using an ACCUPAR ceptometer, model LP-80. Before measurements were taken, an above plot reading was taken. Then a reading at ground level in each sub-sub plot was taken diagonally across the rows. All the 8 sensors were turned on when taking measurements. Measurements were taken on the 29th of January, the 10th of February, 6th of June, 12th of August, and the 2nd of November. Unfortunately, measurements could not be taken from March to May due to Covid-19 Lockdown.

2.9.4 Number of reproductive Seed heads

The number of reproductive seed heads in a 1 m² quadrat in each plot was also counted. From this sample a subsample of 5 reproductive heads was used to determine spikelets per head and seeds per spikelet. The seed-heads not used in the spikelet per head and seed per spikelet counts were frozen in the event that a severe weather event would damage the crop. These could then be used to provide an estimate of what the final seed yield would have been. These measurements were carried out on the 16th of November and then again on the 24th of December just before seed harvest.

2.9.5 Number of Spikelets per Tiller and Seeds per Spikelet

From a subsample of five reproductive tillers the seed heads were counted. Five tillers were used instead of ten as the standard error was similar when only using five tillers. This was determined by running a dummy ANOVA on spikelet per tiller data from one of the main plots. Seeds per spikelets were assessed as the number of seeds in five spikelets on the same five tillers that were used for the seed head counts. These were harvested on the 24th of December and then frozen until after the New Year when they were counted.

2.10 Harvest

2.10.1 Measurements Post harvest

The seed was harvested on the 12th of January 2021. This timing was based on the seed moisture content which was assessed using a Sartorius moisture analyser (model MA160). The paddock was windrowed at an average seed moisture content of 46%. Windrowing was carried out on the 29th of December 2020. Each plot was cut individually, and the biomass was forked into rows so that there was no overlap between rows. The windrower was a Wintersteiger Plot Windrower (Figure 7. and Figure 8.).



Figure 7. Wintersteiger plot windrower used for trial.



Figure 8. Dr Richard Sim operating the Wintersteiger windrower.

The trial was then harvested when seed moisture content was at 15% as assessed using the Sartorius moisture analyser (model MA160). The trial was harvested using a specialised K.W Engineering plot harvester (Figure 9.). Each plot was harvested and bagged individually and tagged for transport back to Kimihia. The trial was harvested on the 12th of January 2021.



Figure 9. Dr Richard Sim and Will Mitchell using the K.W Engineering plot harvester.

2.10.2 Drying and Dressing

After harvest the field dressed seed was then placed on dryers at Kimihia. The seed was dried to an average of 10% across the samples over a period of seven days. The seeds were then dressed using a conventional small seed thresher. Before dressing the seed was weighed to get a field dressed (FD) seed weight. The sample was again weighed after dressing to establish a machine dressed (MD) weight. The machine dressing process began on the 23rd of February 2021.

2.10.3 Thousand Seed Weight

Thousand Seed Weight was measured by using a PFEUFFER Contador 2 Seed Counter to count out 1000 seeds. The thousand seeds were then weighed on conventional scales. This was carried out three times for each sample to generate an average thousand seed weight from the subsample of each plot.

2.11 Statistical Analysis

Data were analysed using the statistical analysis programme GenStat 19th edition. The statistical analysis carried out on each of the datasets was for a split-plot analysis of variance. To ensure the requirements of an ANOVA were met, each dataset was tested for homogeneity and normality. The Fishers protected LSD post-hoc test was used to determine differences between variables. The graphing program Sigma Plot 14.0 was used to create and present figures.

Chapter 3

Results

3.1 Trial 1.

3.1.1 Seed Yield

Field dressed (FD) seed yield was 14% higher in plots left at 14 cm after the initial seed harvest compared to plots mown to 7 cm ($P = 0.038$) (Figure 10.). There were no differences among cutting height treatments ($P = 0.252$).

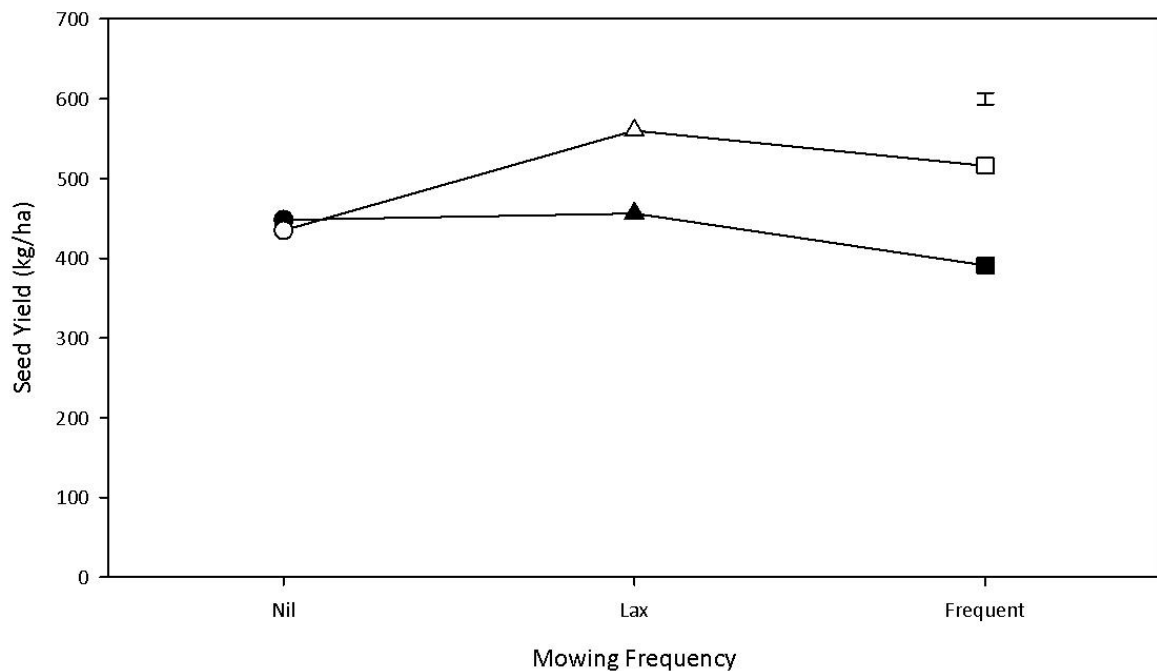


Figure 10. Field dressed seed yield from Trial 1. harvested at a seed moisture content of 15% on the 12th of January 2021. The solid symbols are the plots cut to 7 cm and the hollow symbols are the plots left at 14 cm. The vertical bar is the SEM for comparing cutting height means within either cutting height.

Mowing plots to 7 cm after harvest resulted in a 40% reduction in MD final seed yield compared to plots left at the original harvest height of 14 cm ($P > 0.01$) (Figure 11.). The treatments that produced the highest seed yields were the plots left at 14 cm and

subsequently mown either frequently, or laxly. These treatments produced seed yields of 421 kg/ha and 452 kg/ha respectively. These two yields were not different ($P > 0.05$). The not mowing caused a 53% reduction in seed yield when compared with frequent or lax cut treatments irrespective of mowing height. The lowest seed yield was from the nil mown treatments after plots were initially mowed to 7 cm, with a seed yield of 140 kg/ha.

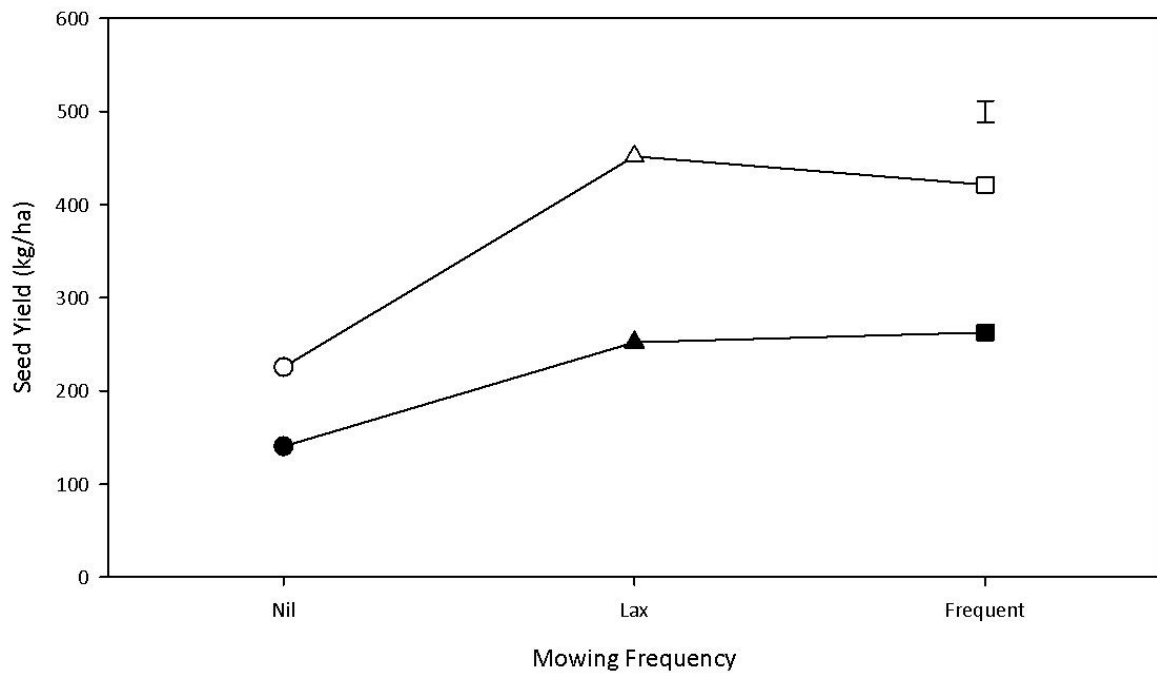


Figure 11. Final machine dressed seed yield from Trial 1. harvested at a seed moisture content of 15% on the 12th of January 2021. The solid symbols are the plots cut to 7 cm and the hollow symbols are the plots left at 14 cm. The vertical bar is the SEM for comparing cutting height means within either cutting height.

The dressing loss was highest in the nil cut plots (Table 9.) with an average dressing loss of 258 kg DM/ha (58%). The frequently cut plots had the lowest dressing loss with an average of 112 kg DM/ha (25%). Plots cut to 7 cm had a 76 kg DM/ha higher dressing loss than plots left at 14 cm after the initial harvest. There was no interaction between mowing height and cutting frequency ($P = 0.493$).

Table 9. FD and MD seed yields, and dressing losses (kg/DM and %) for trial 1.

Effect	Treatment	FD Seed yield (kg/ha)	MD Seed yield (kg/ha)	Dressing loss (kg/ha)	Dressing loss (%)
Cutting height (cm)	7 cm	432 _b	219 _b	213 _a	48 _a
	14 cm	501 _a	366 _a	137 _b	28 _b
	Grand Mean	467	293	175	38
	SEM	14.2	9.0	10.9	1.34
	P Value	0.038	0.001	0.016	0.002
	LSD	63.8	40.5	48.9	6.04
Mowing Frequency	Nil	442 _a	183 _b	258 _a	58 _a
	Lax	508 _a	352 _a	156 _b	32 _b
	Frequent	454 _a	342 _{ab}	111 _b	25 _b
	SEM	28.4	18.4	21.1	3.37
	P Value	0.252	< 0.001	0.001	< 0.001
	LSD	87.6	56.7	64.9	10.4
Interaction	7 cm Nil	448 _a	141 _a	308 _a	69 _a
	7 cm Lax	456 _a	252 _a	204 _a	45 _a
	7 cm Frequent	391 _a	263 _a	129 _a	31 _a
	14 cm Nil	435 _a	226 _a	209 _a	47 _a
	14 cm Lax	560 _a	452 _a	108 _a	19 _a
	14 cm Frequent	516 _a	421 _a	94 _a	18 _a
	SEM	35.8	23.1	26.6	4.12
	P Value	0.222	0.124	0.493	0.399
	LSD	-	-	-	-

Note: Means are separated using Fishers LSD. Means followed by the same letter are similar at the $P < 0.05$ level. Values have been rounded for presentation.

3.1.2 Light Interception

At the January sampling the cutting treatments had not been done and therefore there were no differences in the fraction of light intercepted between the plots cut to 7 cm and the plots left at 14 cm ($P = 0.261$) (Figure 12.).

At the February sampling the fraction of light intercepted was higher in the plots left at 14 cm ($P = 0.018$) compared to the plots cut to 7 cm. There were no differences in the fraction of light intercepted among cutting frequency treatments ($P = 0.101$).

At the June sampling, the lowest fraction of light interception (at 89%) was in the frequently cut plots ($P < 0.001$). The lax and nil cut plots had an average fraction of light interception of 97%. There were no differences in fraction of light intercepted between cutting heights ($P = 0.096$).

In August the fraction of light intercepted was highest at 98% in the lax and nil cut plots ($P < 0.001$), compared to the frequently cut plots which had an average fraction of light intercepted of 91%. There were no differences in light interception between cutting heights ($P = 0.097$). At the November sampling, the plots left at 14 cm and nil mown had the highest fraction of light intercepted at 99% ($P < 0.001$). The cut to 7 cm and nil mown treatment had the next highest fraction of light intercepted at 98%. The cut to 7 cm and laxly cut, and the left at 14 cm and laxly cut treatments were not different from each other. The lowest fraction of light interception was in the frequently cut treatments with an average light interception of 91% (Figure 12.).

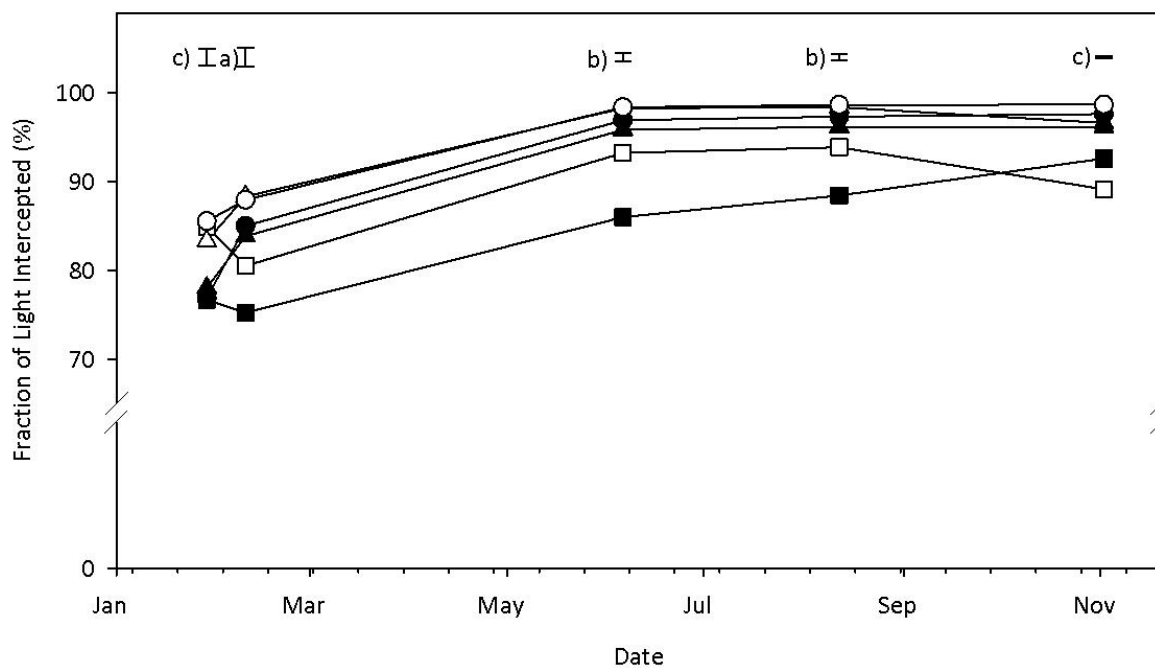


Figure 12. Fraction of light intercepted by the canopy for Trial 1. sampled on the 29th of January, 10th of February, 6th of June, 12th of August, and 2nd of November. Treatments were cut to 7 cm and nil mown (●), laxly mown (▲), or frequently mown (■), and left at 14 cm and nil mown (○), laxly mown (△) or frequently mown (□). The vertical bar a) is the SEM for comparing mowing height, b) is the SEM for cutting frequency and c) is the interaction between both mowing height and cutting frequency.

3.1.3 Biomass cuts

At the January sampling there were no differences in biomass between mowing heights ($P = 0.075$). There were also no differences among cutting frequency treatments ($P = 0.952$) (Figure 13.).

At the February sampling there was 1451 kg DM/ha more on plots left at 14 cm compared to plots cut to 7 cm ($P = 0.017$). There were no differences among cutting frequency treatments ($P = 0.147$).

At the May sampling there was 2032 kg DM/ha more biomass on plots left at 14 cm compared to plots cut to 7 cm ($P = 0.013$). The frequently cut treatments produced the

lowest biomass with an average of 2888 kg DM/ha compared to the nil and lax cut plots with an average of 3678 kg DM/ha ($P = 0.035$).

At the June sampling, the lowest biomass produced was in the mown to 7 cm and cut frequently treatment, with 1963 kg DM/ha ($P = 0.010$). Herbage yield for the cut to 7 cm and laxly or nil mown, and the left at 14 cm and frequently or laxly mown treatments did not differ and had an average biomass of 3979 kg DM/ha. The highest biomass was produced by the left at 14 cm and nil cut treatments with 6106 kg DM/ha (Figure 13.).

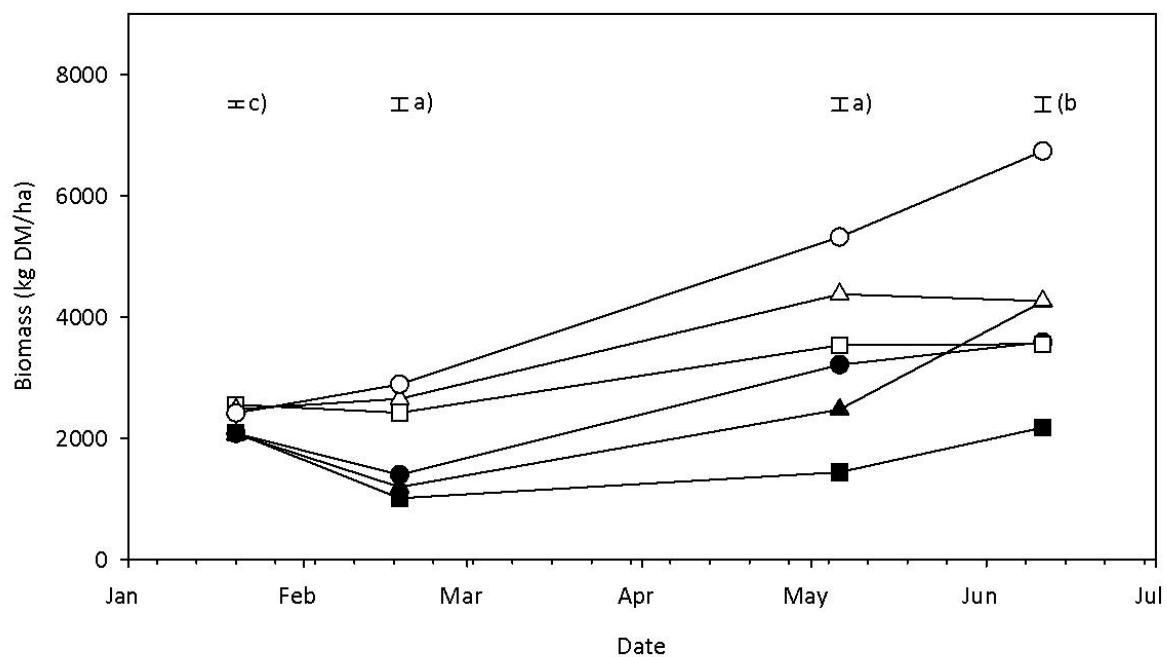


Figure 13. Biomass (kg DM/ha) sampled from Trial 1. on the 20th of January, the 18th of February, the 6th of May, and the 11th of June. Treatments were cut to 7 cm and nil mown (●), laxly mown (▲), or frequently mown (■), and left at 14 cm and nil mown (○), laxly mown (△) or frequently mown. The vertical bar a) is the SEM for comparing mowing height, b) is the SEM for cutting frequency and c) is the pooled SEM of the mean.

3.1.4 Tiller Counts and Sizing

There were no significant differences in vegetative tiller numbers across any of the mowing frequency or cutting height treatments ($P > 0.05$) at all three sampling dates (Table 10.).

Table 10. Vegetative tiller counts per m² from Trial 1. Sampling was carried out on the 6th of June, the 16th of November and the 24th of December.

Cutting		July	November	December
Height	Mowing Frequency	Tillers/m ²	Tillers/m ²	Tillers/m ²
7 cm	Nil	4375 _a	6824 _a	6958 _a
	Lax	5158 _a	6441 _a	7091 _a
	Frequent	5174 _a	7974 _a	6808 _a
	Mean	4902	7079	6952
14 cm	Nil	3483 _a	5291 _a	6399 _a
	Lax	4525 _a	7333 _a	7158 _a
	Frequent	3475 _a	6708 _a	6538 _a
	Mean	3828	6444	6698
	SEM	263.8	417.8	354.5
	P Value	0.706	0.462	0.813

Note: SEM is the standard error of the mean. Values followed by the same letter are similar at $P \leq 0.05$ level.

At the July sampling (Figure 14.) there were no differences in number of tillers in the < 1 mm ($P = 0.138$), 1-2 mm ($P = 0.482$), 3-4 mm ($P = 0.610$), or the 4-5 mm ($P = 0.315$) size categories among any of the treatments. In the 2-3 mm size category the plots cut to 7 cm and not mown had 73% more tillers/m² ($P = 0.001$). There were no differences among cutting frequency treatments for the lax or frequently mown treatments (Figure 14.).

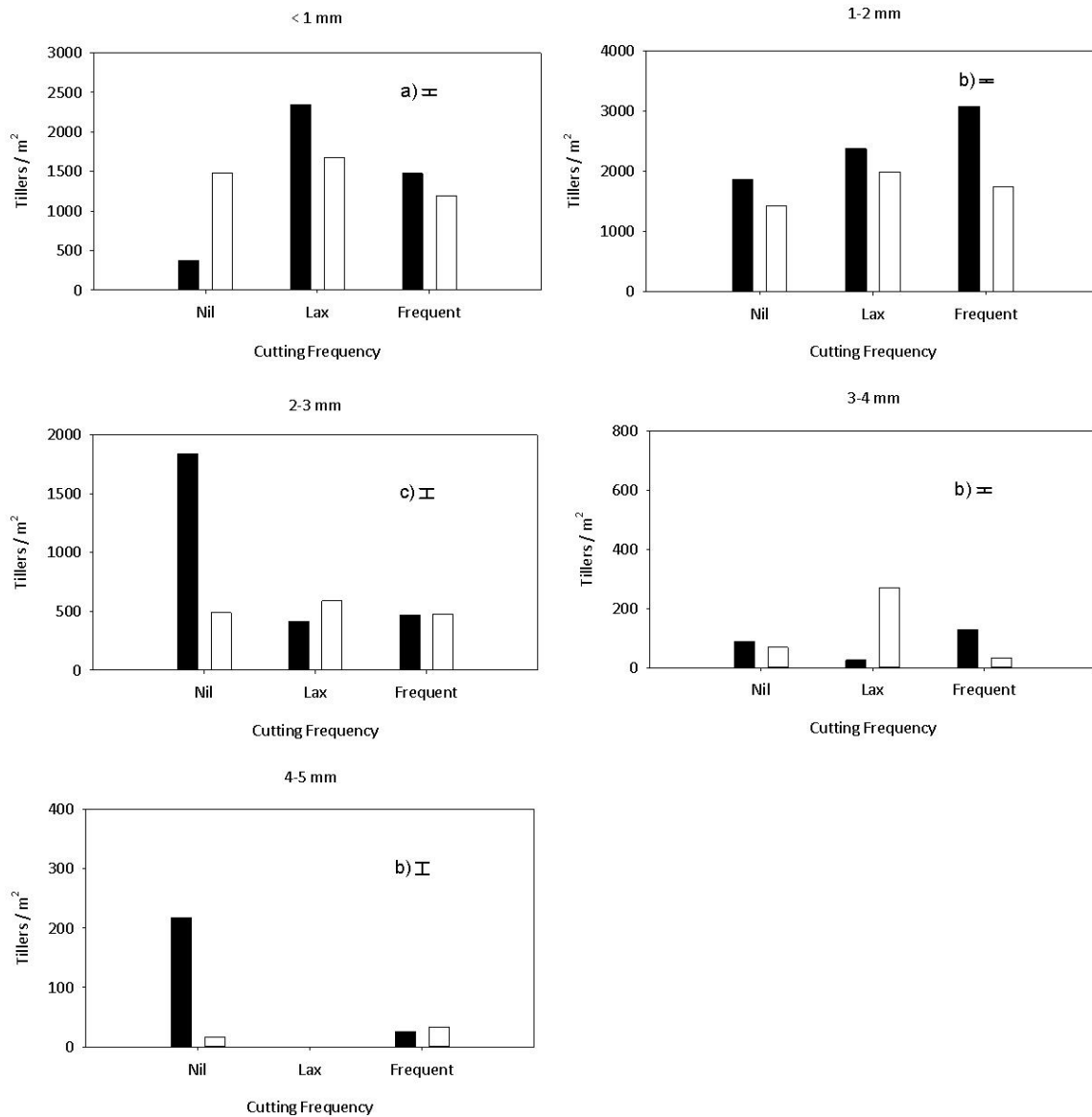


Figure 14. Vegetative tiller counts per m² taken from a subsample and categorised according to size of the tiller 3 mm from the base sampled on the 11th of July. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar a) is the SEM for comparing mowing height, and b) is the pooled SEM of the mean.

At the November sampling (Figure 15.) there were no differences among cutting height or frequency treatments in the <1 mm ($P = 0.941$), 1-2 mm ($P = 0.487$), 2-3 mm ($P = 0.214$), 3-4 mm ($P = 0.438$), or 4-5 mm ($P = 0.248$) size categories.

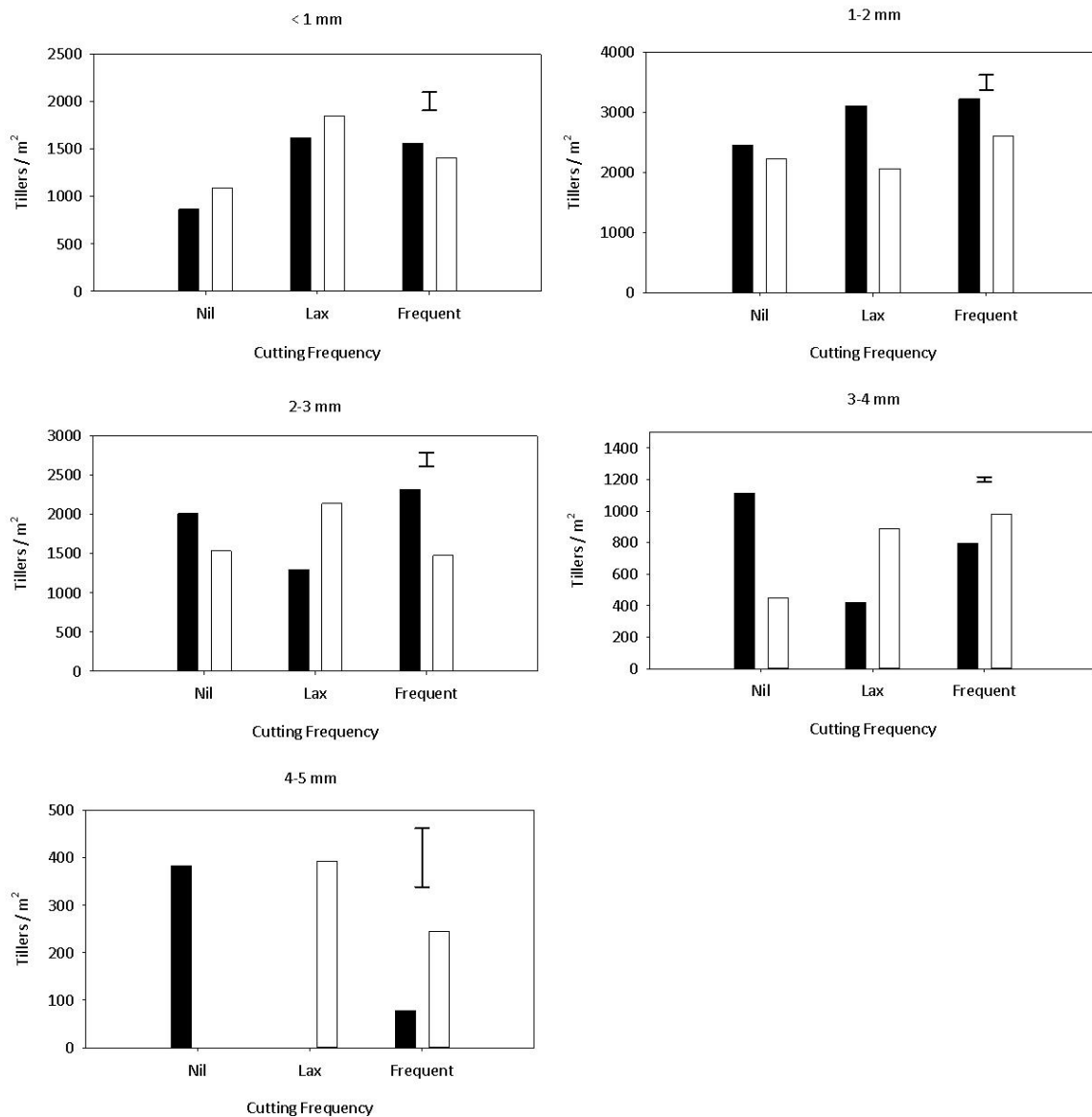


Figure 15. Vegetative tiller counts per m² taken from a subsample and categorised according to size of the tiller 3 mm from the base sampled on the 16th of November. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar is the pooled SEM of the mean.

At the December sampling (Figure 16.) there were no differences between cutting height treatments in the < 1 mm size category ($P = 0.409$). Within this category the frequently cut plots had 58% more tillers than the nil cut plots ($P = 0.044$). The laxly cut plots tillers did not differ from the frequent or nil cut plots. In the 1-2 mm size category the plots cut to 7 cm had 1488 more tillers m² than the plots left at 14 cm ($P = 0.034$). There were no differences among cutting frequency treatments in the 1-2 mm category ($P = 0.856$). In the 2-3 mm size

category there were no differences among any of the treatments ($P = 0.724$). In the 3-4 mm category there were on average 63% more tillers in the nil cut plots compared to the frequent and lax cut plots ($P = 0.025$). There were no differences in tiller number m^2 between mowing heights ($P = 0.156$). In the 4-5 mm size category there were no differences among any of the treatments ($P = 0.144$).

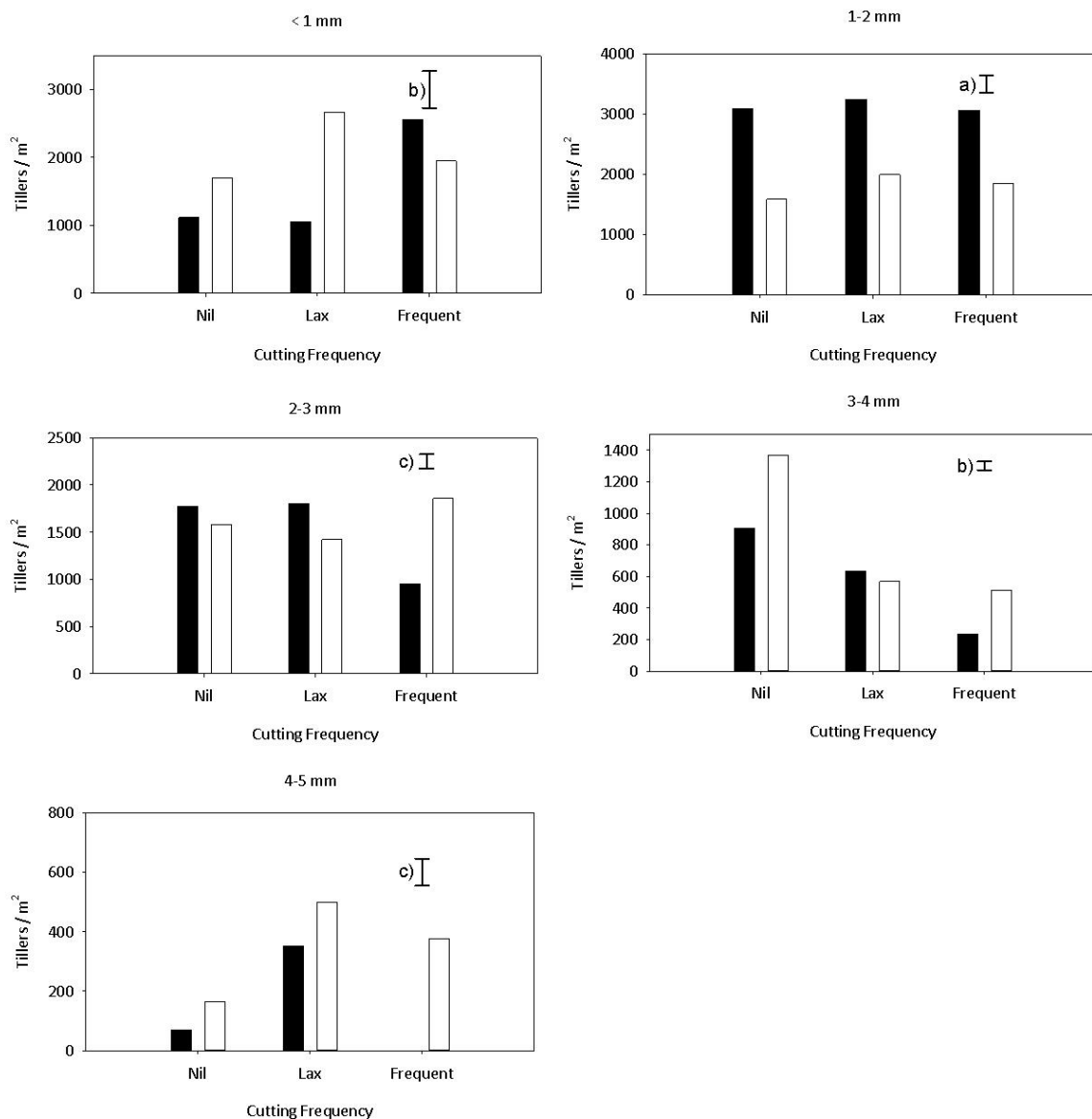


Figure 16. Vegetative tiller counts per m^2 taken from a subsample and categorised according to size of the tiller 3 mm from the base sampled on the 24th of December. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar a) is the SEM for comparing mowing height, b) is the SEM for comparing cutting frequency and c) is the pooled SEM of the mean.

3.1.5 Components of Seed Yield

For reproductive tillers at the November sampling, the plots left at 14 cm had produced on average 54 more reproductive tillers per m² than plots mowed to 7 cm after the initial harvest (Figure 17). The plots left at 14 cm and mown laxly, and the plots cut to 7 cm and mown frequently produced the highest number of reproductive tillers ($P = 0.003$) with 137 and 135 reproductive tillers per m² respectively. There was on average a 46% decline in tiller number in the plots left at 14 cm and nil mown, and the plots cut to 7 cm and either nil or frequently mown when compared with the plots left at 14 cm and laxly or frequently mown.

At the December sampling there was on average a 48% increase in the number of reproductive tillers in the plots left at the original height of 14 cm compared with plots cut to 7 cm ($P = 0.03$) (Figure 17.). The highest number of reproductive tillers were in the plots left at 14 cm and either frequently or laxly mown ($P < 0.001$). There were on average 53% less tillers in the plots cut to 7 cm and mown frequently, laxly or nil compared to plots left at 14 cm and frequently mown ($P = 0.001$).

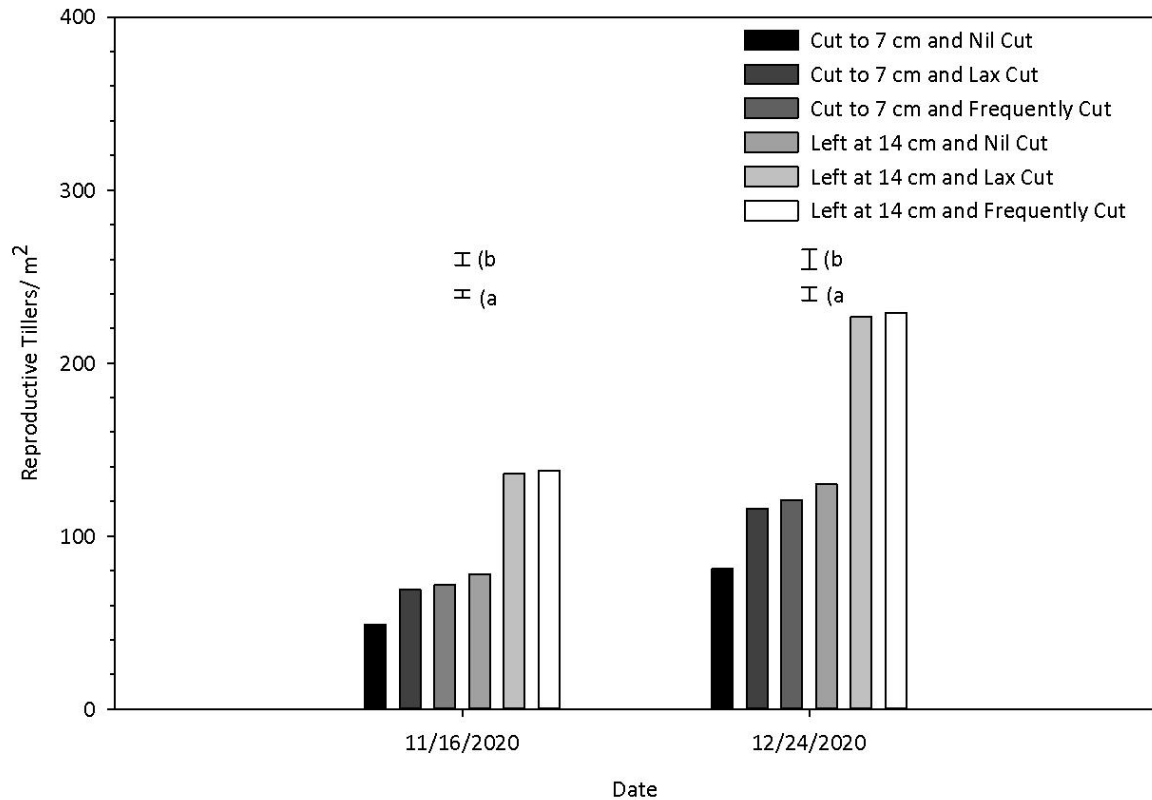


Figure 17. Reproductive tillers per m² sampled on the 16th of November and the 24th of December. The vertical bar a) is the SEM for comparing mowing height, and b) is the SEM for cutting frequency.

There were no differences ($P > 0.05$) in the number of spikelets per seed head, seeds per spikelet, or thousand seed weight under any of the cutting height or mowing frequency treatments (Table 11.).

Table 11. Spikelets per seed head, seeds per spikelet, thousand seed weight (g) (TSW), and harvest index of plants sampled on the 24th of December from trial 1.

Mowing Height	Mowing Frequency	Spikelets per Seed Head	Seeds per Spikelet	TSW (g)	Harvest Index
Cut to 7 cm	Nil	44 _a	4 _a	2.51 _a	1.80 _a
	Lax	54 _a	3 _a	2.58 _a	3.28 _a
	Frequent	44 _a	4 _a	2.32 _a	4.30 _a
	Mean	47.3	4.6	2.47	3.12
Left at 14 cm	Nil	53 _a	3 _a	2.49 _a	2.45 _a

Lax	49 _a	4 _a	2.56 _a	12.28 _a
Frequent	50 _a	3 _a	2.50 _a	5.84 _a
Mean	50.6	3.3	2.51	5.72
SEM	1.603	0.126	0.041	1.21
P Value	0.131	0.426	0.547	0.162

Note: SEM is the standard error of the mean. Values followed by the same letter are similar at $P \leq 0.05$ level.

3.2 Trial 2.

3.2.1 Seed Yield

Field dressed seed yield did not differ between mowing height ($P = 0.067$), or among additional nitrogen fertiliser application timing treatments ($P = 0.408$) (Figure 18.).

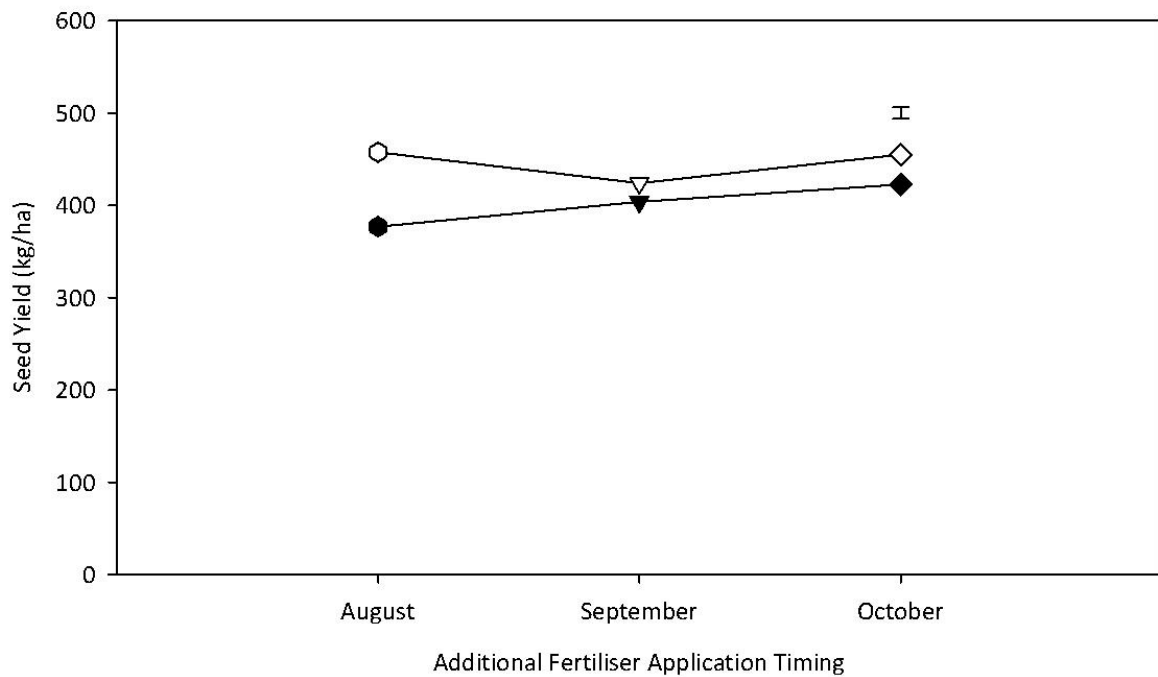


Figure 18. Field dressed seed yield from Trial 2, harvested at a moisture content of 15% on the 12th of January 2021. The solid symbols are the plots cut to 7 cm and the hollow symbols represent the plots left at 14 cm. The vertical bar is the pooled SEM of the mean.

Plots mown to 7 cm had a 22% lower machine dressed seed yield than the plots left at the initial post-harvest height of 14 cm ($P = 0.050$) (Figure 19.). There were no differences among final seed yield for any of the additional fertiliser timing treatments ($P = 0.512$).

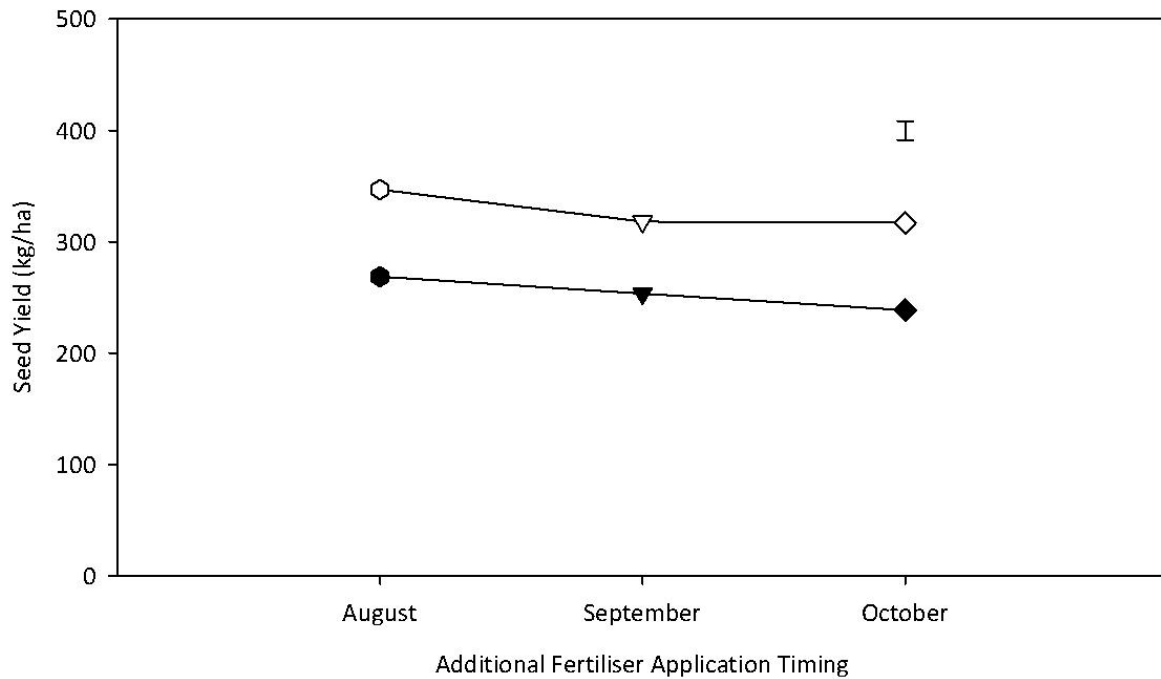


Figure 19. Final machine dressed seed yield from Trial 2, harvested at a moisture content of 15% on the 12th of January 2021. The solid symbols are the plots cut to 7 cm and the hollow symbols represent the plots left at 14 cm. The vertical bar is the SEM for comparing cutting height means within either cutting height.

Dressing losses (kg/ha) were not different between cutting heights ($P = 0.131$) or among fertiliser application timing treatments ($P = 0.976$) (Table 12.). Dressing losses (%) were not different between cutting heights (0.078) or among fertiliser application timing treatments ($P = 0.884$). There was no interaction between cutting heights and fertiliser application timing treatments for dressing loss kg/ha ($P = 0.310$) and dressing loss % ($P = 0.398$).

Table 12. FD and MD seed yields, and dressing losses (kg/DM and %) for trial 2.

Effect	Treatment	FD Seed yield (kg/ha)	MD Seed yield (kg/ha)	Dressing loss (kg/ha)	Dressing loss (%)
Cutting height (cm)	7 cm	401 _a	254 _b	148 _a	37 _a
	14 cm	446 _a	327 _a	118 _a	27 _a
	Grand Mean	424	291	133	32
	SEM	11.17	17.1	10.1	2.58
	P Value	0.067	0.050	0.131	0.078
	LSD	-	72.7	-	-
Fertiliser Application Timing	August	417 _a	286 _a	132 _a	32 _a
	September	414 _a	278 _a	136 _a	41 _a
	October	439 _a	308 _a	131 _a	36 _a
	SEM	13.76	18.4	17.5	4.03
	P Value	0.408	0.512	0.976	0.884
	LSD	-	-	-	-
Interaction	7 cm August	377 _a	253 _a	124 _a	33 _a
	7 cm September	404 _a	239 _a	165 _a	41 _a
	7 cm October	423 _a	269 _a	154 _a	36 _a
	14 cm August	458 _a	318 _a	140 _a	32 _a
	14 cm September	424 _a	317 _a	107 _a	25 _a
	14 cm October	455 _a	347 _a	108 _a	24 _a
	SEM	19.43	27.2	22.6	532
	P Value	0.296	0.955	0.310	0.398
LSD	-	-	-	-	

Note: Means are separated using Fishers LSD. Means followed by the same letter are similar at the $P < 0.05$ level. Values have been rounded for presentation.

3.2.2 Light Interception

At the January sampling (Figure 20.) there were no differences in the fraction of light intercepted between cutting heights ($P = 0.473$). The additional fertiliser application timing treatments had not been applied at this sampling.

At the February sampling, there were no differences in the fraction of light intercepted between cutting heights ($P = 0.519$). The additional fertiliser application timing treatments had not been applied at this sampling.

At the June sampling, the plots left at 14 cm had the highest light interception with an average of 77% light intercepted ($P = 0.007$). The plots cut to 7 cm had an average light interception of 56%. The additional fertiliser application timing treatments had not been applied at this sampling.

At the August sampling the plots left at 14 cm had an average of 85% light interception by the canopy compared to plots cut to 7 cm that had an average light interception of 73% ($P = 0.011$). There were no differences in light interception among fertiliser timing treatments ($P = 0.568$).

At the November sampling, the highest fraction of light intercepted was in the plots left at 14 cm with 97% light intercepted, compared to plots cut to 7 cm with an average light interception of 96% ($P = 0.009$). There were no differences in fraction of light intercepted among fertiliser timing treatments ($P = 0.292$).

The light intercepted declined from February to June under grazing. After closing light interception increased as the crop reached canopy closure (Figure 20.).

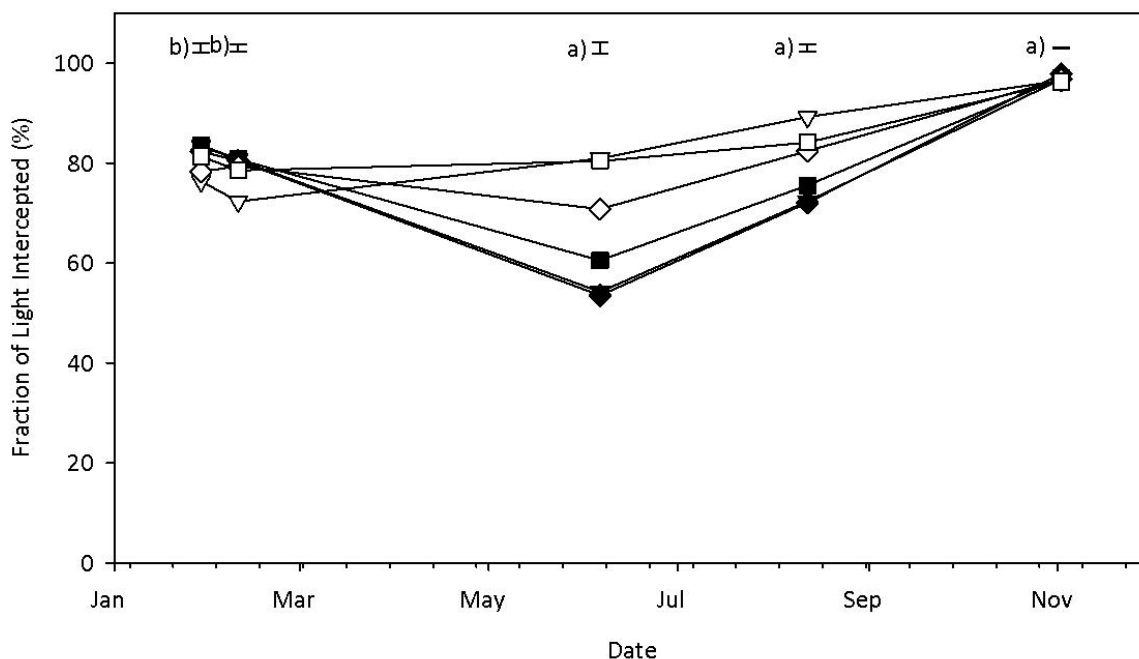


Figure 20. Fraction of light intercepted by the canopy from Trial 2. sampled on the 29th of January, 10th of February, 6th of June, 12th of August, and 2nd of November. Treatments were cut to 7 cm and additional nitrogen fertiliser application in August (●), September (▼), or October (◆), and left at 14 cm and additional nitrogen fertiliser application in August (◊), September (▽) or October (◇). The vertical bar a) is the SEM for comparing mowing height, and b) is the pooled SEM of the mean.

3.2.3 Biomass cuts

At the January biomass cut (Figure 21.) the plots left at 14 cm had an average biomass of 2655 kg DM/ha compared to plots mown to 7 cm with an average biomass of 957 kg DM/ha ($P = 0.002$). At the February cut there was 41% more biomass in plots left at 14 cm compared to plots mown to 7 cm ($P = 0.013$). At the May sampling, the plots cut to 7 cm had 1809 kg DM/ha less than plots left at 14 cm ($P = 0.015$). There were no differences in biomass between cutting height treatments ($P = 0.477$). The additional nitrogen fertiliser application treatments had not yet been imposed when these biomass cuts were taken.

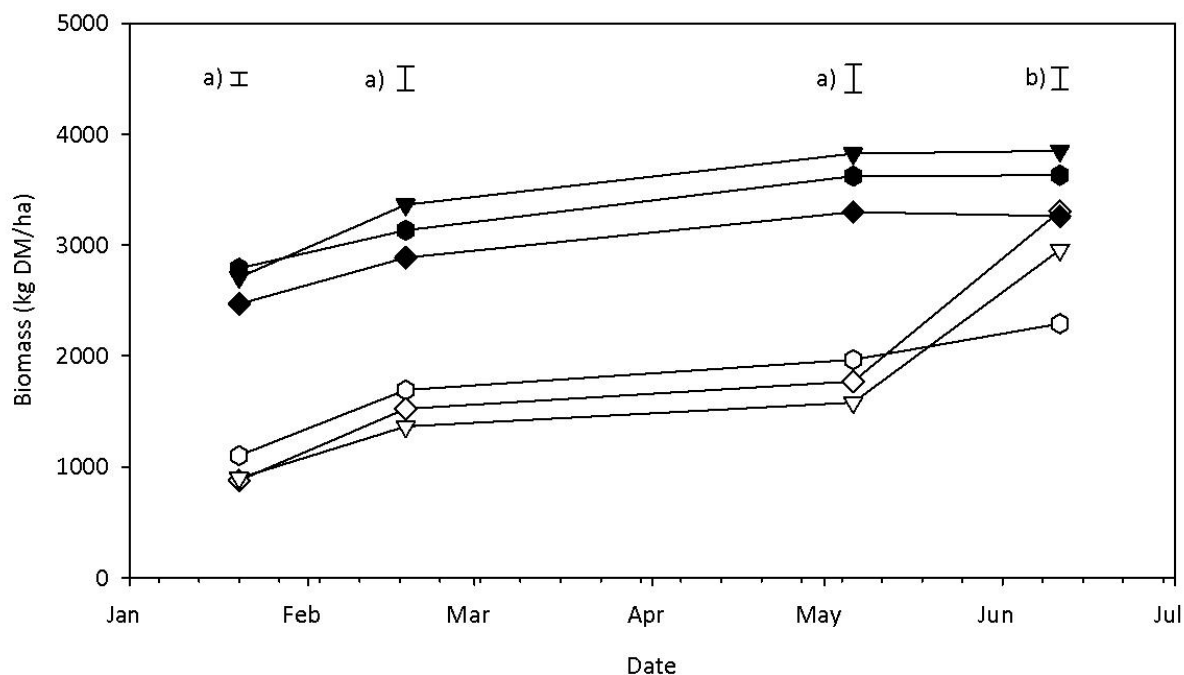


Figure 21. Biomass (kg DM/ha) sampled from Trial 2. on the 20th of January, the 18th of February, the 6th of May, and the 11th of June. The solid symbols are the plots cut to 7 cm and the hollow symbols represent the plots left to 14 cm. The vertical bar a) is the SEM for comparing mowing height, and b) is the pooled SEM of the mean.

3.2.4 Tiller Counts

At the July sampling there was a 32% increase in vegetative tiller number ($P = 0.050$) in plots mown to 7 cm compared with plots left at the initial post-harvest height of 14 cm (Table 13.). The fertiliser treatments had not yet been applied at this sampling. At the November and December sampling there were no differences in vegetative tiller number for any of the treatments ($P > 0.05$) (Table 13.).

Table 13. Vegetative tiller counts per m² from Trial 2. Sampling was carried out on the 6th of July, the 16th of November and the 24th of December. At the July sampling additional nitrogen fertiliser had not yet been applied.

Cutting Height	Fertiliser Application Timing	July Tillers (m ²)	November Tillers (m ²)	December Tillers (m ²)
7 cm	August	8533 _a	7317 _a	9742 _a
	September	-	6533 _a	7850 _a
	October	-	5908 _a	7175 _a
	Mean	8533	6586	8255
14 cm	August	5789 _b	6442 _a	6850 _a
	September	-	5867 _a	8233 _a
	October	-	7233 _a	6950 _a
	Mean	5789	6514	7344
LSD Height		2860	-	-
LSD Fertiliser Treatment		-	-	-
SEM		659.8	220.1	368
P Value		0.048	0.114	0.950

Note: Means are separated using Fishers LSD. LSD is the least significant difference for the main effect of N. SEM is the standard error of the mean. Values followed by the same letter are similar at P ≤ 0.05 level.

At the July sampling (Figure 22.) there were no differences among any of the cutting height or additional fertiliser application timings in the < 1 mm (P = 0.266), 1-2 mm (P = 0.559), 2-3 mm (P = 0.499), 3-4 mm (P = 0.391), or 4-5mm (P = 0.391) size tiller categories. At this sampling the fertiliser timing treatments had not yet been applied (Figure 22.).

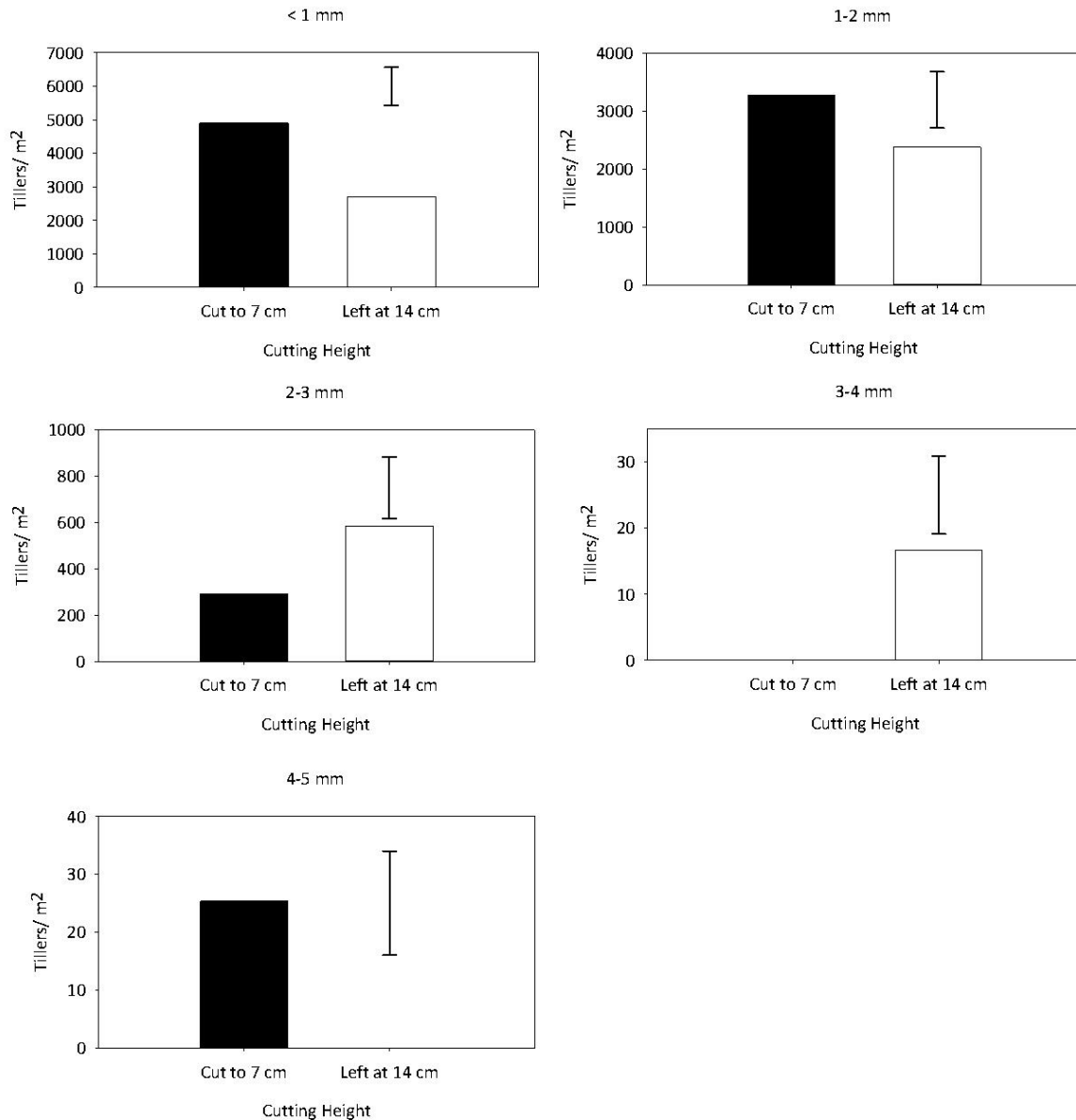


Figure 22. Vegetative tiller counts per m² taken from a subsample from Trial 2. and categorised according to size of the tiller 3 mm from the base sampled on the 6th of July. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar is the pooled SEM of the mean.

At the November sampling (Figure 23.) in the < 1 mm size category there were 42% more tillers in the plots cut to 7 cm compared to the plots left at 14 cm ($P = 0.002$). There were no differences among nitrogen fertiliser application timings ($P = 0.316$). In the 1-2 mm size category the plots cut to 7 cm with a November fertiliser application had the highest number of tillers (3982 tillers m², $P = 0.008$). There were no differences among the other

treatments. In the 2-3 mm size category there were no differences among any of the treatments ($P = 0.068$). In the 3-4 mm size category there were 88% more tillers in the plots left at 14 cm compared to the plots cut to 7 cm ($P = 0.008$). In the 4-5 mm size category there were no differences among treatments ($P = 0.093$) (Figure 23.).

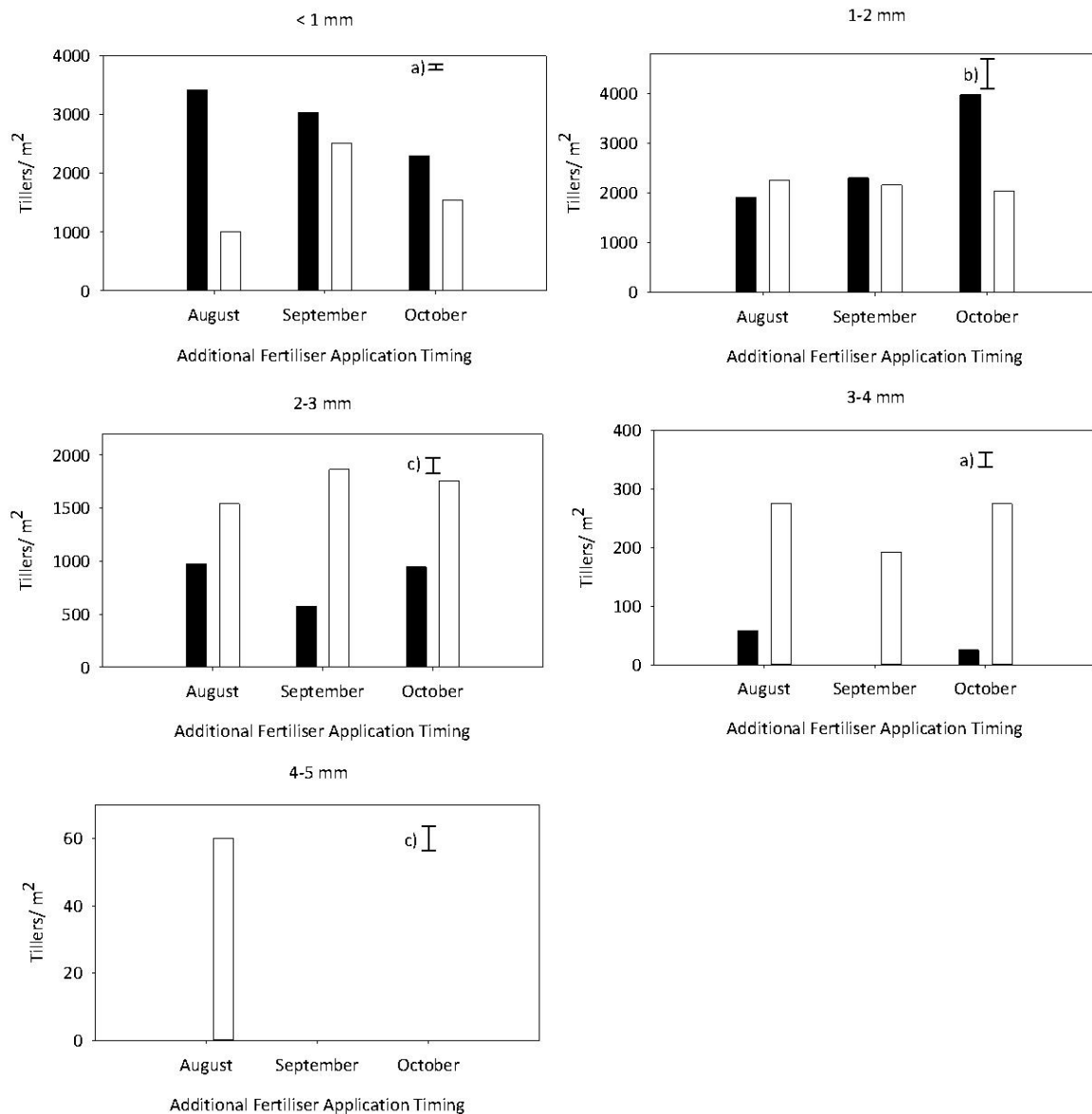


Figure 23. Vegetative tiller counts per m² taken from a subsample from Trial 2. and categorised according to size of the tiller 3 mm from the base sampled on the 16th of November. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar a) is the SEM for comparing cutting heights, b) for the SEM for comparing the interaction between treatments and c) the pooled SEM of the mean.

At the December sampling (Figure 24.) there were no differences among any of the cutting height or additional fertiliser application timings in the < 1 mm ($P = 0.794$), 1-2 mm ($P = 0.423$), 2-3 mm ($P = 0.302$), 3-4 mm ($P = 0.941$), or 4-5mm ($P = 0.313$) size categories.

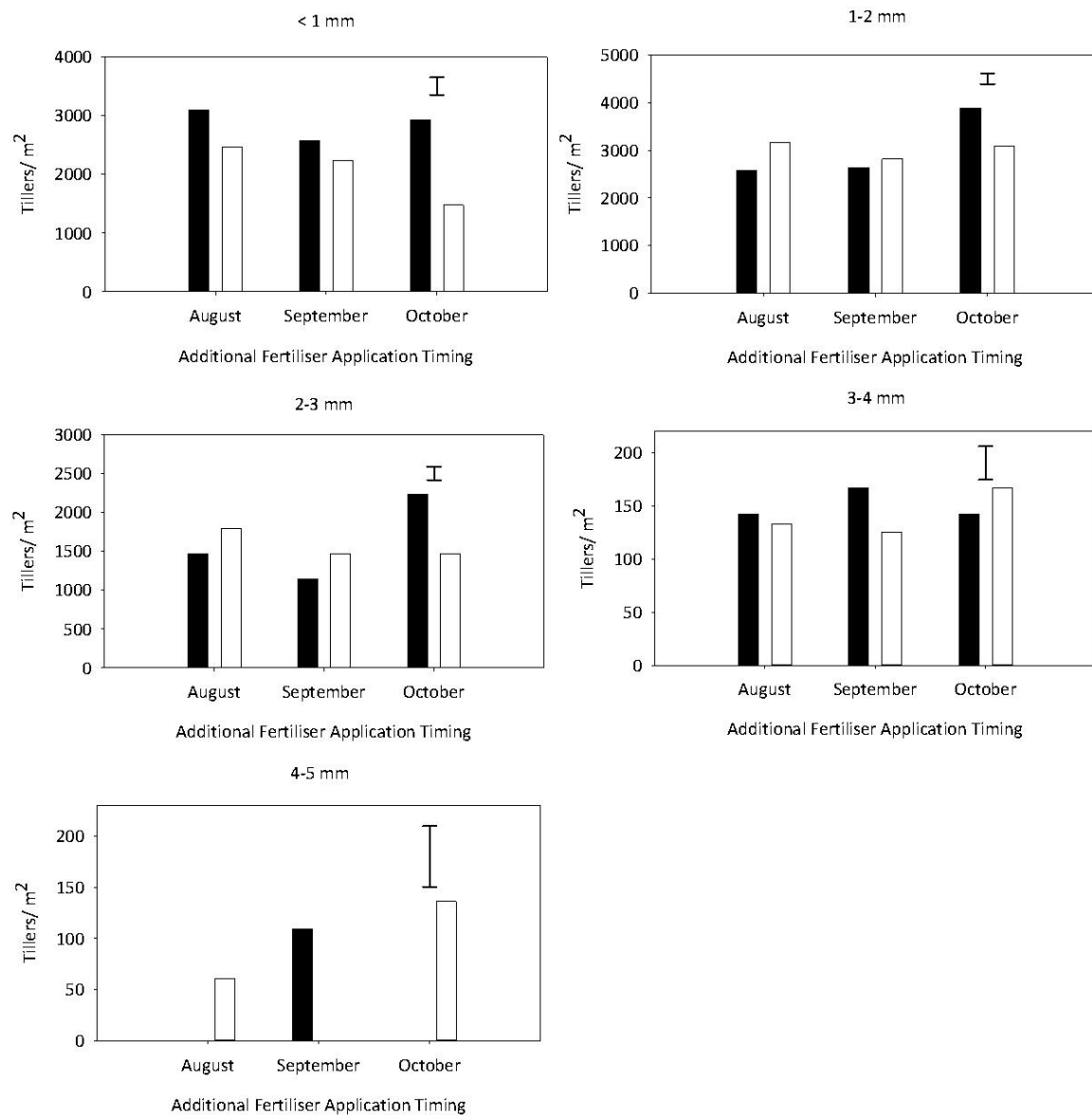


Figure 24. Vegetative tiller counts per m² taken from a subsample from Trial 2. and categorised according to size of the tiller 3 mm from the base sampled on the 24th of December. The black bars are the plots cut to 7 cm and the white bars are the plots left at 14 cm. The vertical bar is the pooled SEM of the mean.

3.2.5 Components of Seed Yield

There were no differences in reproductive tiller number per m² among any of the treatments (Figure 25.) at the November tiller counts ($P = 0.693$). At the December tiller count there were 33% more reproductive tillers per m² in plots left at 14 cm compared to plots cut to 7 cm ($P = 0.034$). There were no differences in reproductive tiller number among fertiliser application timing treatments at the November ($P = 0.875$), or December ($P = 0.157$) sampling dates (Figure 25.).

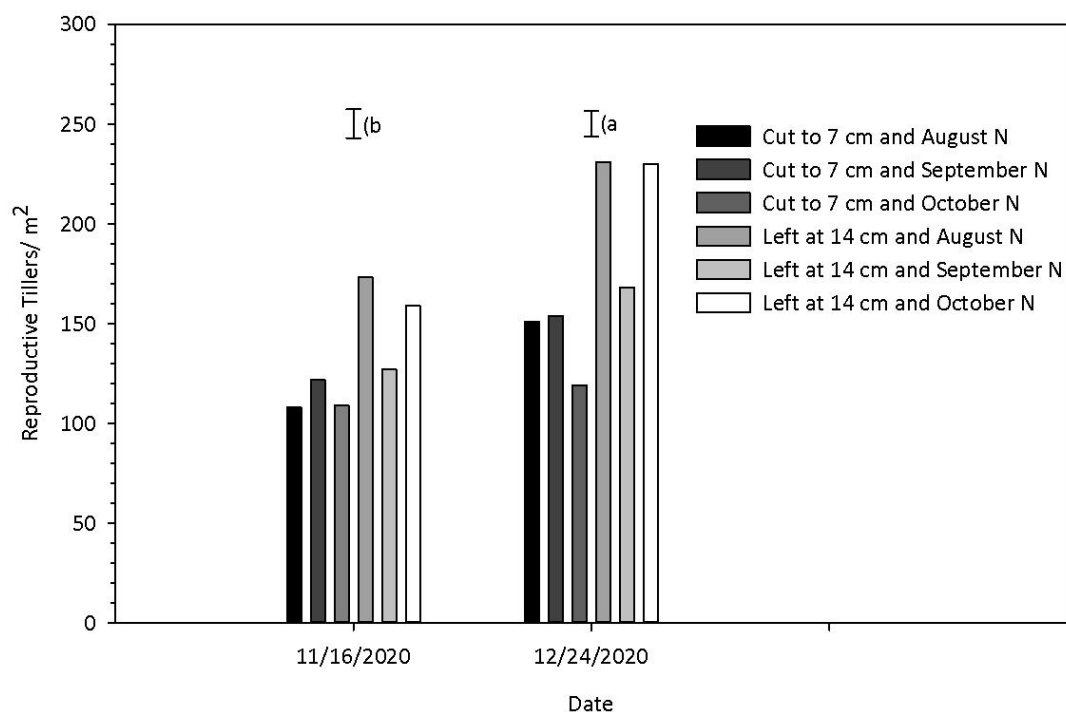


Figure 25. Reproductive tiller number sampled on the 16th of November and the 24th of December from Trial 2. The vertical bar a) is the SEM for comparing cutting heights, and b) is the pooled SEM of the mean.

There were no differences in spikelets per seed head across any of the treatments ($P = 0.552$). There were also no differences in seeds per spikelet ($P = 0.308$). There were no differences in harvest index among any of the treatments ($P = 0.052$). Thousand seed weight was on average 7% higher in plots left at 14 cm compared with plots cut to 7 cm post-harvest ($P = 0.029$).

Table 14. Spikelets per seed head, seeds per spikelet, thousand seed weight (g) (TSW), and harvest index sampled on the 24th of December from trial 2.

Cutting Height	Fertiliser		Spikelets per Seed Head	Seeds per Spikelet	TSW (g)	Harvest Index
	Application	Timing				
7 cm		August	49 _a	3 _a	2.27 _b	3.08 _a
		September	55 _a	3 _a	2.22 _b	3.12 _a
		October	51 _a	4 _a	2.38 _b	3.01 _a
		Mean	52	3	2.29	3.07
14 cm		August	51 _a	3 _a	2.53 _a	4.00 _a
		September	42 _a	3 _a	2.48 _a	4.41 _a
		October	49 _a	3 _a	2.33 _a	4.76 _a
		Mean	47	3	2.45	4.39
		SEM	1.998	0.113	0.028	0.232
		P Value	0.552	0.308	0.029	0.052

Note: SEM is the standard error of the mean. Values followed by the same letter are similar at $P \leq 0.05$ level.

Chapter 4

General Discussion

Under a cutting regime the residue management practice of leaving the crop residue at 14 cm after seed harvest produced 40% higher machine dressed (MD) seed yields in the subsequent crop than mowing the plots to 7 cm (Figure 11.). The same trend was observed with the field dressed (FD) results showing a 14% higher seed yield in plots left at the initial harvest height of 14 cm. Under a grazing post-harvest residue management final seed yield was on average 23% higher in plots left at 14 cm compared with plots mown to 7 cm after harvest. The FD results showed no differences among mowing height or cutting frequency treatments. This contradicted the initial expectation that by mowing to open the sward, this would allow more light into the canopy and therefore increase final seed yield. The initial hypothesis presumed that under short canopies there would be a higher rate of light available for absorption at the crown and therefore more tillers would be produced. This hypothesis was proposed based on the findings of Williamson et al. (2012), who found that there was a direct correlation between light interception and tiller initiation. It was assumed that the higher number of tillers available for vernalisation and therefore reproductive initiation would correlate to higher final seed yields.

In trial 1 dressing losses were 20% higher in plots cut to 7 cm than plots left at 14 cm after the initial harvest. This could have been due to plots mown to 7 cm having much smaller tillers. Langer (1979) found that smaller tillers that took longer to go reproductive typically had smaller seeds. Anslow (1964) found that in perennial ryegrass (*Lolium perenne*), a close relative of tall fescue, tillers with heads that appeared two weeks later than the rest of the sward had significantly smaller seeds. Smaller seeds are typically dressed out in the machine dressing process which would explain the higher dressing losses in the plots cut to 7 cm. The nil cut plots had the highest dressing losses with a loss of 258 kg/ha which was 14% higher than the lax or frequently cut plots. This could have been due to the density of the crop causing shading. Shading of lower tillers reduces the leaf area index (LAI) available for light interception. A study by Griffith (2000) found that for third year tall fescue crops that had

lodged (reducing LAI available for photosynthesis), there was 23% lower seed mass (mg) on average compared to plants that remained upright. This would explain the higher dressing loss in the nil cut plots as the smaller seeds would have been dressed out. In Trial 2 there were no differences in dressing losses between mowing heights after the initial harvest. This suggests that although plots cut to 7 cm had smaller thousand seed weights than plots left at 14 cm, the seeds were not small enough to be dressed out.

Treatments left at 14 cm and mown frequently or laxly did produce higher seed yields than the other treatments but still had relatively “low” yields. Tall fescue seed yields in Canterbury can range anywhere from 170 kg/ha to 1630 kg/ha (Hare et al., 1990). The crop had met the temperature requirements for vernalization as it was vernalized (below 10°C) for 1612 hours. Hare (1992) found that a vernalisation period of 1440 hours was sufficient for 100% of the tall fescue plants in a population to go reproductive. There is variation within cultivars due to genetic diversity of tall fescue populations that make it hard to use a blanket recommendation, but the Volupta crop in Barrhill exceeded the requirement Hare (1992) found, by 172 hours so can be considered to have been effectively vernalised. The crop was exposed to 13 weeks of short days (less than 12 hours of daylight) after closing. Bean (1970) found that for 90% of tall fescue plants to flower they needed to be exposed to 8-12 weeks of short days. This suggests that the crop’s obligate short day requirement for reproductive initiation had been met.

Both trials differed from other similar studies in that the residue was retained on the crop after the initial harvest. There was an average of 1500 kg DM/ha of stubble returned to the crop. The residue being returned could have contributed to the low seed yields from both trials irrespective of treatments. A study by Young et al. (1998) showed returning residue produced 107 less vegetative tillers m² and 68 less fertile tillers m² compared with a propane burning treatment. This decline in seed yield when residue is retained could be due to shading of the lower tillers. Shading of lower tillers reduces the leaf area index (LAI) available for light interception for tillers lower in the canopy. This reduces the non-structural carbohydrate reserves in the stem that are required for the plants to go reproductive.

In trial 1 there were no differences in total vegetative tiller number per m² across the July, November, and December samplings. At the July sampling date there were no differences between treatments for the tillers in the <1 mm, 1-2 mm, 3-4 mm or 4-5 mm size categories ($P > 0.05$). In the 2-3 mm size category the mown to 7 cm and nil mown treatment produced 505 more tillers m² than the other treatments ($P = 0.001$). It was expected that the nil cut treatments would have higher numbers of tillers of greater sizes as they were never cut. It was surprising that the plots left at 14 cm and nil mown did not also have higher tiller numbers in the 2-3 mm size category. This could have been due to the taller plants shading the base of the tillers due to the dense canopy (Williamson et al., 2012). At the November sampling there were no differences in number of tillers m² for any of the treatments across any of the size categories.

At the December sampling in the 1-2 mm size category the short treatments (cut to a post-harvest height of 7 cm) had 38% more tillers m² ($P = 0.050$) than the tall plots (left at a post-harvest height of 14 cm). In the 2-3 mm size category the plots cut to 7 cm and frequently mown treatment had 45% less tillers than the cut to 7 cm and laxly or nil mown, and the left at 14 cm and frequently, laxly, or nil mown treatments ($P = 0.050$). In the 3-4 mm category the left to 14 cm and nil cut treatment had 33% more tillers than the other treatments ($P = 0.025$). These differences could be attributed to stem carbohydrate reserves. The stem width near the base of the tiller can be used as an indicator of carbohydrate reserves as the tiller base is typically where carbohydrates are stored (White, 1973). Non-structural stem carbohydrates are required for growth and development of the plants, and are a product of photosynthesis (Jones, 2013). When plants have insufficient assimilatory reserves for growth and development these carbohydrate reserves are depleted (Jones, 2013). This could explain why at the December sampling in the 1-2 mm size category there were more tillers in the plots cut to 7 cm. With less photosynthetic tissue available for light interception, there would be less carbohydrate reserves stored. This was also reflected in the 2-3 mm size category where the treatment that produced the lowest number of tillers were the plots cut to 7 cm and frequently mown. After a defoliation event in grasses, fructose reserves in the stem are rapidly depleted (Sullivan and Sprague, 1943). As the plots were frequently defoliated this suggests that the tillers may not have been able to recover. A study by Volenec (1986) showed a 50% decline in stem carbohydrate reserves four days

after a defoliation event while the plant recovered. After 24 days total non-structural carbohydrates within the stem reach 93% of their initial levels.

Carbohydrate stem reserves are a product of photosynthesis (Jones, 2013). Therefore, light interception is the main factor controlling the production of these assimilates. In Trial 1. at the January sampling, the plots left at the initial harvest height of 14 cm were able to intercept 7% more light than plots cut to 7 cm ($P = 0.022$) (Figure 12.). This was also observed at the February sampling with plots left at 14 cm able to intercept 5% more light than plots cut to 7 cm. This was to be expected as most of the tissue above 7 cm is typically leaf rather than stem (Jones, 2013). Over the winter period the fraction of light intercepted was lowest in the frequent cut treatment at 91% compared with the average light interception of the lax and nil treatments at 97% ($P < 0.001$). When photosynthesis is not sufficient to meet demands for growth and development the stored carbohydrates are used. This is due to the plant prioritising growth over carbohydrate storage (Jones, 2013). This suggests that when plants are cut to 7 cm and then mowed frequently the plant is not able to recover enough photosynthetic tissue to an extent where it is able to produce enough carbohydrates to exceed demand.

Under grazing (Trial 2.) the fraction of light intercepted was highest at the plots mown to 14 cm after the initial harvest ($P = 0.01$). The additional spring nitrogen timing treatments did not show any differences ($P > 0.05$). This suggests that the timing of the spring nitrogen is less influential than application rate. As the trial had already had 197 kg/ha of nitrogen fertiliser there was likely enough nitrogen in the system and delaying the spring fertiliser application until October would not have had a measurable effect. Nitrogen has a strong impact on the rate of tiller production in grass swards. A study by Mazzanti (1994) found that with an application rate of 360 kg N ha annually there was a 22% increase in tiller density from 4686 to 5712 tillers m^2 . This is because nitrogen acts as a stimulant for tiller initiation and survival, but does not influence the proportion or tillers that then go fertile (Langer, 1979). A study by Fairey (1998) looked at the effect that nitrogen fertiliser application timings had on the components of seed yield, and was found that fertile tiller number, harvest index and thousand seed weight did not differ with different application

times. The same trend occurred in Trial 2, where no differences were found in number of seeds per spikelet, or spikelets per seed head for the nitrogen fertiliser application timings. As Fairey (1998) mentioned this could likely be due to the crop already having a high utilization of N from that applied during the autumn.

Trial 2 was under the management practice of grazing. At the July sampling, the plots mowed to 7 cm had 2744 tillers m² more than plots mown to 14 cm after the initial harvest ($P = 0.048$). The additional spring nitrogen treatments had not been imposed at this point. This higher tiller number suggests that in the plots mown to 7 cm there was a higher level of incident radiation intercepted at the crown. A study by Williamson et al. (2012) found that an increase in the red-far red light ratio caused a 25% increase in the number of buds resulting in tillers in a variety of C₃ grasses. At the July sampling there were no differences in the number of tillers in any of the size categories. This was to be expected as the sward was very dense with rigid stems, so stock did not graze into the base of the plant. They were only grazing leaf tissue therefore would not have had a significant effect on tiller production. Biomass in Trial 2 stayed relatively consistent and only varied by 540 kg/ha from February to June. This reinforces the point that the livestock were only grazing to the height that the crop had been mown to. Biomass in trial 2 was consistently higher in plots left at 14 cm compared to plots mown to 7 cm. There was on average across all samplings of 1753 kg/DM more on plots left at 14 cm than plots mown to 7 cm.

At the November sampling in the < 1 mm size category the plots mown to 7 cm with a September additional fertiliser application and an October fertiliser application had the highest numbers of small tillers ($P = 0.041$). Plots left at 14 cm with an October N application treatment had the lowest number of tillers in the 1-2 mm size category. In the 1-2 mm size category the cut to 7 cm with an August N application treatment produced the highest number of tillers ($P = 0.009$). In the 2-3 mm size category the plots left to 14 cm had the highest number of tillers ($P = 0.036$). The plots left to 14 cm also had the highest number of tillers in the 3-4 mm category. The only treatment that had any tillers in the 4-5 mm size category were the plots left at 14 cm with a September N application. Under grazing the same trends were observed with the mowing height treatments. The plots mown to 7 cm had more of the smaller tillers (> 2 mm) and the plots left at 14 cm had more of the larger

tillers (< 2 mm). This follows the same trend as a study by Matthew et al. (2000). They found that at lower mowing heights there was a higher density of small tillers whereas at higher mowing heights there was a higher density of larger tillers. At the December sampling there were no differences in number of tillers for any of the size categories ($P > 0.05$).

Biomass in Trial 1 was higher in the plots left at the initial harvest height of 14 cm (Figure 13.) at the autumn and winter samplings ($P < 0.001$). The July tiller counts did not show any differences ($P > 0.05$) suggesting that most of the biomass was leaf tissue rather than tillers. The length of new leaves and their rate of appearance is strongly influenced by the length of the leaf sheath below (Jones, 2013). This explains the higher biomass in the plots left at 14 cm. At all sampling dates biomass was highest in the treatment with plots left at 14 cm and nil mown (Figure 13.).

The left at 14 cm and nil mown treatment produced on average 280 more tillers than any of the other treatment in the 3-4 mm size category ($P = 0.025$). It was to be expected that leaving the crop at 14 cm would produce larger tillers as there was a greater leaf area for light interception and therefore would have been greater carbohydrate reserves, which can be assumed by measuring the base of the tiller (White, 1973). Contrary to this the nil cut plots produced a 53% lower seed yield ($P < 0.001$) than plots that were mown either frequently or laxly (Figure 11.). This could have been a result of lodging. Lodging reduces the ability of the plant to effectively photosynthesise and respond to environmental cues through shading of lower tillers. A study by Griffith (2000) found that in a tall fescue seed crop, plots that had lodged had 127 mg of seed per fertile tiller less than plots where lodging did not occur. The same study also found a 63% reduction in stem water soluble carbohydrates in plants that had lodged compared to plants that remained upright. Unfortunately lodging was not assessed in this research but would be beneficial to look at in the future to confirm this theory.

Hare (1992) found that when tillers are exposed to shaded conditions new tillers would fail to initiate, or the reproductive fertility of the tiller would be 50% less than tillers not exposed to shaded conditions. This suggests that although the plant needs to have enough stem carbohydrates available to go reproductive, the environmental cues still need to be

met. Most reproductive tillers were found on the edges of the drill rows and the tramlines (Figure 26.). This observation also reinforces the point that shading reduced reproductive tiller initiation. Future research could look at assessing the positioning of tillers within the drill row to see if that influences seed yield.



Figure 26. Photo taken on the 24th of December at the trial site of the tramlines showing reproductive tillers on the edges of the tramlines.

Spikelets per seed head ($P = 0.131$), seeds per spikelet ($P = 0.426$) and TSW (thousand seed weight) ($P = 0.547$) had not differed among treatments in Trial 1. This suggests that under a cutting regime these are not the most influential components of seed yield for the tall fescue cultivar *Volupta*. November reproductive tillers were 46% higher in plots left at 14 cm ($P < 0.001$) compared with plots mown to 7 cm. The same trend was observed at the December sampling date. Reproductive tiller number was highest in plots left at 14 cm compared to plots mown to 7 cm ($P = 0.003$). This reinforces that the plants left at 14 cm had more photosynthetic tissue left behind, therefore were able to intercept more light for generation of stem carbohydrate reserves need for reproductive initiation. Once initiation has occurred reproductive activity consumes up to 50% of the total available carbohydrates (Jones, 2013). Nofal et al. (2004) found that there was a direct correlation between intensity of defoliation and the non-structural carbohydrate stem reserves in the tillers. A study by

Brougham (1957) found that crops defoliated to 12.5 cm only took four days to regain full light interception and therefore replenish carbohydrate reserves whereas crops defoliated below 7.5 cm took up to 24 days. This suggests that the crops left at 14 cm after mowing were able to recover carbohydrate reserves in around four days compared to the crops mown to 7 cm that could have taken up to 24 days. As mowing occurred around every 30 days it was likely crops mown to 7 cm were never able to replenish reserves and were in a constant deficit. This explains the consequential lower seed yields. Heineck et al. (2020) found a direct positive correlation ($R^2 = 0.8$) between fertile tiller number and final seed yield. This reinforces the point that reproductive tiller number is one of the most influential components of seed yield (Wang et al., 2011).

In Trial 2, there were no differences in reproductive tiller number at the November sampling ($P = 0.693$). At the December sampling, the highest number of reproductive tillers were in the plots left at 14 cm ($P = 0.034$). There were no differences across any of the treatments for the number of spikelets per seed head ($P = 0.552$), and seeds per spikelet ($P = 0.308$), and harvest index ($P = 0.052$). This reinforces the point mentioned above that for the cultivar *Volupta* of tall fescue these are not the most influential components of seed yield. The plots left at 14 cm produced the highest thousand seed weights (TSW) with an average of 2.45 g compared to the plots cut to 7 cm that had an average TSW of 2.29 g ($P = 0.031$). This was to be expected as the plots cut to 7 cm the highest number of small tillers (below 2 mm width), and small tillers typically produce smaller seeds (Langer, 1979).

4.1 Conclusion

This study demonstrated how influential post-harvest residue management of a tall fescue seed crop is on the very dense forage cultivar *Volupta*. The initial hypothesis was that by mowing to open the sward, this would allow more light into the canopy and therefore increase final seed yield. The results contradicted this in that the plots mown to 7 cm produced significantly lower seed yields than plots mown to 14 cm after the initial harvest. What was not considered in the initial hypothesis was the carbohydrate reserves that a plant requires to be able to go reproductive. Removing the majority of the leaf when the plots were cut to 7 cm and then frequently mowing the plant was constantly depleting the

stem carbohydrate reserves and they were therefore unable to recover. The same results occurred with grazing. Livestock grazed to the height the plots had been cut to. As the grazing trial was set stocked the plants were never able to recover their carbohydrate reserves. The study also demonstrated that there are multiple factors that influence the final seed yield. Nil cut plots produced the overall lowest seed yield even though they likely had the required carbohydrate reserves. This suggests environmental factors such as shading were the cause of this lower seed yield.

This research showed important differences between cutting treatments and showed that post-harvest management is essential for improving seed yield. This trial also highlighted the factor of whether it is worthwhile to keep a third-year tall fescue seed crop. The highest seed yield observed from both trials was 435 kg/ha. The first-year seed crop of this paddock produced a seed yield of 1500 kg/ha. This drop in seed yield is not solely related to this cultivar and has been well documented in tall fescue (Rolston and Young, 2009).

4.2 Recommendations

This trial provided valuable insight into how *Volupta* tall fescue yielded under a variety of different post-harvest residue management. Due to tall fescue's self-incompatibility mechanisms, swards are very diverse and closer to ecotypes rather than cultivars. As a result, the findings from this study are likely cultivar specific and the trial would need to be replicated on a variety of ecotypes to see if the same trends are observed. Therefore, only generalised recommendations can be made.

Under a cutting regime the plots left at 14 cm and frequently or laxly mown produced the highest final seed yields. This suggests that there would be no impact on seed yield whether one, or multiple balage cuts were taken in a season as long as the residue was left at 14 cm. Under a grazing system yields were highest when the crop was left at 14 cm after the initial harvest and stocked under a set stocking regime. The stock will only graze to the point where the grass was initially cut post-harvest, and therefore grazing should not reduce seed yields. This may differ for a softer leaf tall fescue as the stock will be able to penetrate deeper into the crop.

It could not be recommended to growers to keep a tall fescue seed crop for a third year based on the decline in seed yields from year 1 – 3. The highest seed yields of 435 kg/ha would not be financially viable for a grower to continue with this crop.

4.3 Future Research

Future research could look at replicating the trial on different cultivars. It would be interesting to also research the influence of germplasm location on how the plant responds to reproductive cues.

Research is very limited on the vernalisation and photoperiod requirements in tall fescue, so future research could look at using germplasm from a variety of regions to develop a framework for recommendations to growers.

Future research could also look at measuring the carbohydrate stem reserves to determine the main compounds that affect seed yield. The shoot to root ratio and carbohydrate partitioning could also be looked at.

Light interception measurements at different heights within the canopy could also provide insight into at what level shading will reduce reproductive initiation. Research into the maximum tiller density before shading will reduce seed yield would also be beneficial.

Future research could also look at replicating this trial with residue removed to see how much of an impact retaining residue had on the final seed yields.

The cause of the decline in seed yield for third year tall fescue seed crops could also be studied to determine whether it is possible to prevent this.

References

- Anderson, N., Sullivan, C., Chastain, T., and Garbacik, C. (2016). Examining possible benefits of plant growth regulator mixtures in tall fescue seed crops. *Seed production research* **4**, 3-6.
- Anderson, N. P., Chastain, T. G., Hart, J. M., Young, W. C., and Christensen, N. W. (2014). Tall fescue grown for seed: A nutrient management guide for western Oregon. *Oregon State University Extension Service*.
- Anslow, R. (1964). Seed formation in perennial ryegrass: II. Maturation of seed. *Grass and forage science* **19**, 349-357.
- Bahmani, I. (1999). Tiller dynamics and leaf growth processes of the perennial ryegrass cultivars "Ellett" and "Grasslands Ruanui" as influenced by environmental factors: a thesis in partial fulfilment of the requirements for the degree of Doctor of Philosophy (Ph. D.), Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand.
- Barker, D., Lancashire, J., and Meurk, C. (1985). Grasslands Wana'cocksfoot-an improved grass suitable for hill country. In "Proceedings of the New Zealand Grassland Association", Vol. 46, pp. 167-172.
- Bean, E. (1970). Short-day and low-temperature control of floral induction in *Festuca*. *Annals of Botany* **34**, 57-66.
- Brock, J., Anderson, L., and Lancashire, J. (1982). 'Grasslands Roa'tall fescue: seedling growth and establishment. *New Zealand Journal of Experimental Agriculture* **10**, 285-289.
- Brougham, R. (1957). Some factors that influence the rate of growth of pasture. In "Proceedings of the New Zealand Grassland Association", Vol. 19, pp. 109-116.
- Callow, M. N., Lowe, K. F., Bowdler, T. M., Lowe, S. A., and Gobius, N. R. (2003). Dry matter yield, forage quality and persistence of tall fescue in a subtropical environment. *Australian Journal of Experimental Agriculture* **43**, 1093-1099.
- Canode, C. L. (1972). Grass seed production as influenced by cultivation, gapping, and postharvest residue management. *Agronomy Journal* **64**, 148-151.
- Canto, M., Pancera, E., Neto, A. B., Bremm, C., Vier, P., and Costa, A. (2020). Effects of nitrogen fertilisation and irrigation on seed yield and yield components of signal grass (*Urochloa decumbens*). *Crop and Pasture Science* **71**, 294-303.
- Casal, J., Sacher, R., and Deregibus, V. (1987). Tillering responses of *Lolium multiflorum* plants to changes of red/far-red ratio typical of sparse canopies. *Journal of Experimental Botany* **38**, 1432-1439.
- Charles, G. W., Blair, G. J., and Andrews, A. C. (1991). The effect of sowing time, sowing technique and post-sowing weed competition on tall fescue (*Festuca arundinacea* Schreb.) seedling establishment. *Australian Journal of Agricultural research* **42**, 1251-125R.
- Chastain, T., Kiemnec, G., Cook, G., Garbacik, C., Quebbeman, B., and Crowe, F. (1997). Residue management strategies for Kentucky bluegrass seed production. *Crop Science* **37**, 1836-1840.
- Chastain, T. G., Young III, W. C., Garbacik, C. J., Meints, P. D., and Silberstein, T. B. (2000). Alternative residue management and stand age effects on seed quality in cool-season perennial grasses. *Seed Technology* **22**, 34-42.

- Chilcote, D. O., and Youngberg, H. W. (1975). Propane flamer burning of grass seed field stubble. *Agronomic Crop Science Report*, 3-5.
- Cohan, F. M. (2009). Tracking bacterial responses to global warming with an ecotype-based systematics. *Clinical Microbiology and Infection* **15**, 54-59.
- Dai, X., Wang, Y., Dong, X., Qian, T., Yin, L., Dong, S., Chu, J., and He, M. (2017). Delayed sowing can increase lodging resistance while maintaining grain yield and nitrogen use efficiency in winter wheat. *The Crop Journal* **5**, 541-552.
- Davies, A. (1965). Carbohydrate levels and regrowth in perennial rye-grass. *The Journal of Agricultural Science* **65**, 213-221.
- Easton, H. S., Lee, C. K., and Fitzgerald, R. D. (1994). Tall fescue in Australia and New Zealand. *New Zealand Journal of Agricultural Research* **37**, 405-417.
- Fairey, N., and Lefkovitch, L. (1998). Effects of method, rate and time of application of nitrogen fertilizer on seed production of tall fescue. *Canadian Journal of Plant Science* **78**, 453-458.
- Fairey, N., and Lefkovitch, L. (1999). Crop density and seed production of tall fescue (*Festuca arundinacea* Schreb). 1. Yield and plant development. *Canadian Journal of Plant Science* **79**, 535-541.
- Fairey, N., and Lefkovitch, L. (2001). Effect of post-harvest management on seed production of creeping red fescue, tall fescue, and Kentucky bluegrass in the Peace River region of north-western Canada. *Canadian Journal of Plant Science* **81**, 693-701.
- France, S. d. (2014). Fetuque élevée demi-tardive Volupta. (S. d. France, ed.), 62 rue Léon Beauchamp.
- Griffith, S. (2000). Changes in dry matter, carbohydrate and seed yield resulting from lodging in three temperate grass species. *Annals of Botany* **85**, 675-680.
- Hare, M. (1992). Seed production in tall fescue (*Festuca arundinacea* Schreb.): a thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Seed Technology at Massey University, Palmerston North, New Zealand.
- Hare, M. (1993). Post-harvest and autumn management of tall fescue seed fields. *New Zealand Journal of Agricultural Research* **36**, 407-418.
- Hare, M. (1994). Autumn establishment of three New Zealand cultivars of tall fescue (*Festuca arundinacea* Schreb.) for seed production. *New Zealand Journal of Agricultural Research* **37**, 11-17.
- Hare, M. (1998). Establishment, spacing density and grazing effect. *NZGA: Research and Practice Series* **5**, 9-19.
- Hare, M., Rolston, M., Archie, W., and McKenzie, J. (1990). 'Grasslands Roa' tall fescue seed production: research and practice. In "Proceedings of the New Zealand Grassland Association", Vol. 52, pp. 77-80.
- Hare, M., Rolston, M., Falloon, R., and Hickson, R. (1988). Autumn sowing date and seeding rate affect seed production of prairie grass. *Journal of Applied Seed Production* **6**, 46-54.
- Hart, J. M., Anderson, N. P., Hulting, A. G., Chastain, T. G., Mellbye, M. E., Young, W. C., and Silberstein, T. B. (2012). Postharvest residue management for grass seed production in western Oregon.
- Heineck, G. C., Ehlke, N. J., Altendorf, K. R., Denison, R. F., Jungers, J. M., Lamb, E. G., and Watkins, E. (2020). Relationships and influence of yield components on spaced-plant and sward seed yield in perennial ryegrass. *Grass and Forage Science* **75**, 424-437.

- Hickey, M. (1990). Seed production of "Grasslands Roa" tall fescue in Southland. *In* "Proceedings of the New Zealand Grassland Association", Vol. 52, pp. 111-113.
- Hirel, B., and Krapp, A. (2020). Nitrogen Utilization in Plants I Biological and Agronomic Importance. *In* "Reference Module in Life Sciences". Elsevier.
- Holman, J. D., Hunt, C., Johnson-Maynard, J., VanTassel, L., and Thill, D. (2007). Livestock use as a non-thermal residue management practice in kentucky bluegrass seed production systems. *Agronomy Journal* **99**, 203-210.
- Huijser, P., and Schmid, M. (2011). The control of developmental phase transitions in plants. *Development* **138**, 4117-4129.
- Innes, G. (2003). Tall Fescue. *AgFact* **4**, 2-7.
- Jewiss, O. R. (1972). Tillering in grasses-it's significance and control. *Grass and Forage Science* **27**, 65-82.
- Jones, M. (2013). "The grass crop: the physiological basis of production," Springer Science & Business Media, New York.
- Langer, R. H. M. (1979). Growth of grass plant in relation to seed production. *NZGA: Research and Practice Series* **1**, 6-11.
- Liang, S., Xi, L., and Wang, J. (2012). Chapter 16 - Vegetation Production in Terrestrial Ecosystems. *In* "Advanced Remote Sensing" (S. Liang, X. Li and J. Wang, eds.), pp. 501-531. Academic Press, Boston.
- Martiniello, P. (1998). Influence of agronomic factors on the relationship between forage production and seed yield in perennial forage grasses and legumes in a Mediterranean environment. *Agronomie* **18**, 591-601.
- Matthew, C., Assuero, S., Black, C., and Sackville Hamilton, N. (2000). Tiller dynamics of grazed swards. *Grassland Ecophysiology and Grazing Ecology*, 127-150.
- Mohlenbrock, R. H. (2002). "Grasses, bromus to paspalum," 2/Ed., Southern Illinois.
- Nofal, H. R., Sosebee, R. E., Wan, C., Borrelli, J., Zartman, R., and McKenney, C. (2004). Mowing rights-of-way affects carbohydrate reserves and tiller development. *Rangeland Ecology and Management* **57**, 497-502.
- Patel, A., Tiwari, S., Parihar, P., Singh, R., and Prasad, S. M. (2019). Chapter 2 - Carbon Nanotubes as Plant Growth Regulators: Impacts on Growth, Reproductive System, and Soil Microbial Community. *In* "Nanomaterials in Plants, Algae and Microorganisms" (D. K. Tripathi, P. Ahmad, S. Sharma, D. K. Chauhan and N. K. Dubey, eds.), pp. 23-42. Academic Press, Allahabad, India.
- Rolston, M., Clifford, P., Charlton, J., Hampton, J. G., White, J., Wright, A., and Knox, D. (1990). New Zealand's herbage seed industry: an overview. *In* "Proceedings of the New Zealand Grassland Association", Vol. 52, pp. 55-58.
- Rolston, M., McCloy, B., and Pyke, N. (2004). Grass seed yields increased with plant growth regulators and fungicides. *In* "Proceedings of the New Zealand Grassland Association", Vol. 66, pp. 127-132.
- Rolston, M. P., and Young, W. C. (2009). Seed production. *Tall Fescue for the Twenty-first Century* **53**, 407-426.
- Sadras, V., and Calderini, D. (2009). "Crop physiology: applications for genetic improvement and agronomy," Academic Press, New York.
- Santillano-Cázares, J., Redfearn, D., Caddel, J., Goad, C., and Hopkins, A. (2008). Winter grazing can be beneficial to tall fescue seed production in Oklahoma. *Forage & Grazinglands* **6**, 1-6.

- Silva, N., and Goring, D. (2001). Mechanisms of self-incompatibility in flowering plants. *Cellular and Molecular Life Sciences* **58**, 1988-2007.
- Small, C. C., and Degenhardt, D. (2018). Plant growth regulators for enhancing revegetation success in reclamation: A review. *Ecological Engineering* **118**, 43-51.
- Steiner, J., Mueller-Warrant, G., Griffith, S., Banowetz, G., and Whittaker, G. (2006). Conservation practices in western Oregon perennial grass seed systems: II. Meadowfoam rotation crop management. *Agronomy Journal* **98**, 1501-1509.
- Sullivan, J., and Sprague, V. (1943). Composition of the roots and stubble of perennial ryegrass following partial defoliation. *Plant Physiology* **18**, 656.
- Templeton, W., Mott, G., and Bula, R. (1961). Some effects of temperature and light on growth and flowering of tall fescue, *Festuca arundinacea* Schreb. II. floral development 1. *Crop Science* **1**, 283-286.
- Thompson, B. (2014). Chapter Nine - Genetic and Hormonal Regulation of Maize Inflorescence Development. In "Advances in Botanical Research" (F. Fornara, ed.), Vol. 72, pp. 263-296. Academic Press, East Carolina.
- Volaire, F., Norton, M., and Lelièvre, F. (2009). Summer drought survival strategies and sustainability of perennial temperate forage grasses in Mediterranean areas. *Crop Science* **49**, 2386-2392.
- Volenec, J. (1986). Nonstructural carbohydrates in stem base components of tall fescue during regrowth. *Crop Science* **26**, 122-127.
- Wang, Q., Hu, T., Cui, J., Wang, X., Zhou, H., Han, J., and Zhang, T. (2011). Modelling of seed yield and its components in tall fescue (*Festuca arundinacea*) based on a large sample. *African Journal of Biotechnology* **10**, 12584-12594.
- Waring, R. H., and Running, S. W. (2007). CHAPTER 2 - Water Cycle. In "Forest Ecosystems (Third Edition)" (R. H. Waring and S. W. Running, eds.), pp. 19-57. Academic Press, San Diego.
- White, L. M. (1973). Carbohydrate reserves of grasses: a review. *Rangeland Ecology & Management/Journal of Range Management Archives* **26**, 13-18.
- Williamson, M. M., Wilson, G. W., and Hartnett, D. C. (2012). Controls on bud activation and tiller initiation in C3 and C4 tallgrass prairie grasses: the role of light and nitrogen. *Botany* **90**, 1221-1228.
- Young, W. C., Gingrich, G. A., Silberstein, T. B., and Quebbeman, B. M. (1998). Post-harvest residue management of creeping red and chewings fescue seed crops. *Agronomy Journal* **90**, 69-73.
- Young, W. C., Mellbye, M. E., and Silberstein, T. B. (1999). Residue management of perennial ryegrass and tall fescue seed crops. *Agronomy Journal* **91**, 671-675.
- Young, W. C., Quebbeman, B., Silberstein, T. B., and Chilcote, D. O. (1994). Evaluation of equipment used by Willamette Valley grass seed growers as a substitute for open-field burning. *Oregon State University Extension Service*.