# Optimizing Oat Yield, Quality and Stand-ability in Central Alberta

by

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# Abstract

The value of oat (*Avena sativa* L.) for the producer is a function of both grain yield and quality. Therefore, managing nitrogen fertilizer rates to optimize yield while meeting expected grain quality standards is essential in guaranteeing profitable production. To determine the effect of nitrogen fertilization on grain yield and quality, field studies were conducted at Barrhead and St. Albert, AB over a three-year period (2014–2016) to determine responses to four nitrogen fertilizer rates (5, 50, 100, 150 kg $ha^{-1}$) on five oat cultivars differing widely in agronomic traits. Grain yield, grain quality and β-glucan content of oat were measured. Application of nitrogen fertilizer resulted in a significant increase in grain yield, plant height and lodging score. Grain quality such as test weight and plump kernel decreased with greater nitrogen fertilizer rates. Average β-glucan content differed between cultivars. Optimizing oat yield and quality for high-value markets may be achieved by selecting well adapted cultivars and N fertility rates.

The use of the plant growth regulator (PGR) trinexapac-ethyl has been shown to reduce lodging in cereal crops. Plant growth regulators of interest in Canadian cereal cropping systems are intended to restrict plant height and thereby reduce lodging susceptibility. Experiments were conducted over a three-year period (2014–2016) to determine the effect of trinexapac-ethyl application and nitrogen fertilization on yield, lodging and related agronomic responses of oat. The experiment was arranged in a randomized complete block with four replicates. The treatments consisted of four trinexapac-ethyl application rates (0, 70, 100 and 130 g a.i $ha^{-1}$) and four nitrogen rates (5, 50, 100 and 150 kg $ha^{-1}$), on the cultivar Stride. Grain yield, plant height, lodging score and grain quality parameters were evaluated. Grain yield was unaffected by applications of trinexapac-ethyl. Plant height was reduced by 5% to 16% with increasing rates of trinexapac-ethyl. PGR application had a significant effect on lodging at two experimental sites, where the severity of lodging was reduced 12% to 31% with high rates PGR application. The rates of nitrogen influenced grain yield, height and lodging. Using PGRs to maintain grain yield and avert lodging are necessary only under conditions where lodging represents a substantial risk.

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## Contribution of Authors

The contributions made by the candidate and co-authors to the conclusion of this work are described here in.

The thesis literature review, introduction and conclusion was written by the candidate with the editorial assistance of Dr. Linda Hall.

Chapter three of this thesis was written by the candidate, with editorial assistance from Dr. Linda Hall, and statistical consultation from Dr. Vagner Leite. The candidate conducted trials at St. Albert, compiled data, conducted statistical analysis and writing of the manuscript. Dr. Sheri Strydhorst was responsible for conducting trials at Barrhead with the help of her technical staff. William May, Agriculture and Agri-Food Canada conducted trials at the Indian Head site. Dr. Linda Hall, Dr. Sheri Strydhorst and Mr. Keith Topinka played a key role in trial design. Dr. Vagner Leite provided statistical analysis support.

Chapter four was written by the candidate with the editorial assistance of Dr. Linda Hall. The candidate was responsible was conducting trials in St. Albert, data compilation, statistical analysis and writing of manuscript. Dr. Sheri Strydhorst and Mr. William May were responsible for conducting trials at their respective locations with the help of their technical staff. Technical and field support in chapter three and four was provided by Mr. Keith Topinka, Ms. Lisa Raatz, Ms. Elise Martin, Mrs. Judy Irving as well as other graduate students in the weed science program.

Dr. Linda Hall was the graduate student supervisor for the candidate and worked with candidate in the writing of manuscripts, experimental designs and advised the candidate throughout the program.

# Table of contents

# List of Tables

# List of Figures

## List of Abbreviations

| | |
|---|---|
| ANOVA | analysis of variance |
| CDP | copalyl diphosphate |
| CPP | copyl pyrophosphate |
| EU | European Union |
| FPP | farenosyl pyrophosphate |
| GGPP | geranylgeranyl pyrophosphate |
| GS | growth stage |
| LTA | long term average |
| MVA | mevalonic acid |
| OM | organic matter |
| PGA | D-glyceraldehyde 3-phosphate |
| PGR | plant growth regulator |
| TKW | thousand kernel weight |

# Chapter One: Introduction

## 1.1. Background

Canada produced 2,907,000 tonnes of oat (*Avena sativa* L.) in 2014 (Statistics Canada, 2014), with the bulk of production taking place in the Prairie provinces. The annual acreage of oats in western Canada has increased in the last three decades (Statistics Canada, 2004), largely attributed to improved yields, grain quality, disease resistance and market demand. Alberta oat production was estimated at 533,600 tonnes in 2014, with an average yield of 2930 kg ha $^{-1}$ (Agri-Food Statistics Update, 2014). In 2014, oat in Alberta was seeded on 271,139 hectares (3.5% of cultivated crop area), lower than wheat and barley with 2,757,932 and 1,335,462 hectares respectively. The lack of regionally specific oat research has been a factor leading to relatively low acreage and yields in central and northern Alberta, despite the high yield potential and available local oat markets. Profitability is driven by yield and quality parameters including grain protein, oil content, plumpness, thousand kernel weight, test weight and proportion of thin oats that determine grade and market opportunity. Oats are partitioned into end-use markets primarily determined by quality and cultivar. There are four end use markets; performance, feed, milling and hulless oat (Alberta Agriculture, 2010). Milling oats are primarily use for human consumption, whereas feed oat is used mainly as feed for cattle and other livestock. Performance oats are processed for animal consumption, particularly race horses. The main objective of acquiring oat of high milling quality is to obtain grain that will produce a high-quality product and a high milling yield. There are minimum quality standards set for milling oat in western Canada. Milling oats standards vary with the buyer, but requirements for high quality include: maximum moisture content of 15%; a minimum test weight of 245 g/0.5 L; a minimum 1000 grain weight of 27 g; 26% maximum hull content; minimum 90% plump kernels; double oat not to exceed 0.8%; a 1% allowable foreign material and maximum foreign grain of 3% (Ganssmann and Vorwerck, 1995).

There is renewed interest in the usefulness of oat β-glucan in human diets. Dietary fiber constitutes a vital part of a healthy diet and β-glucans are one of the essential fractions of soluble dietary fiber. β-Glucans have attracted much attention for their functional properties (Brennan and Cleary 2005; Wood 2007). Oat contains 4-8% oil (Winfield et.al 2007), lower concentrations are required for milling oat for human consumption. β-glucans are natural polymers made up of glucose molecules linked together by a series of beta-(1, 3) and (1, 4) linkages, comprising a class of non-digestible polysaccharides called βeta-D-glucans (Daou and Zhang, 2012). In oat, β-glucan is found mainly in the endosperm and the subaleurone layer (Wood, 1993). Among cereals, oat and barley have the greatest concentrations of β-glucan (Wood, 1994; Åman and Hesselman, 1985; Prentice et al. 1980). Oat products are a good source of water-soluble dietary fiber because of their high β-glucan content, palatability, and relatively low cost. Various studies have documented the cholesterol lowering effects of β-glucan in humans (Davidson et al. 1991). Oat β-glucan has strong cholesterol and triglyceride lowering properties leading to reduced cardiovascular diseases (Daou and Zhang, 2012). Anderson et al. (1991) demonstrated that oat bran containing β-glucan, reduced total serum cholesterol in hypercholesterolemic subjects as much as 23% without a change in high-density lipoprotein (HDL) cholesterol. It is imperative to understand the influence of genetic, agronomic and environmental factors on oat β-glucan content in order to increase β-glucan content of commercial oat cultivars. An environmental factor which may influence grain β-glucan content and other traits is available soil nitrogen. Elevated soil nitrogen levels result in increased grain yield, plant height, straw yield, lodging score, and groat protein content. Moreover, high soil nitrogen has been reported to decrease kernel weight and harvest index (Frey, 1959; Brinkman and Rho, 1984). Nitrogen fertilization has been reported to have no effect on β-glucan content of oat in Canada (Humphreys et al. 1994). Redaelli et al. (2013) reported that location, cultivar, and their interaction, had significant effects on the β-glucan content.

Nitrogen strongly affects oat yield and grain quality (Chalmers et al. 1998; May et al. 2004; Mohr et al. 2007); increasing nitrogen fertilizer asymptotically increases yield (Brunner and Freed 1994). As with the economic theory of diminishing returns, a simple asymptotic or quadratic plateau yield curve indicate the first increments of fertilizer are used very effectively followed by decreasing and eventually negligible responses for subsequent increments. A typical nitrogen response curve in oats, shows maximum yields associated with nitrogen rates above 80 kg $ha^{-1}$ (Brinkman and Rho, 1984; Marshall et al. 1987, May et al. 2004). Though higher yields may be attained from high nitrogen inputs, oat quality such as high test weight could be compromised. Reduction in test weight, kernel weight and percent plump kernels, and increases in percent thin kernels have resulted from increasing nitrogen fertilizer rates in several studies (Marshall et al. 1987; Jackson et al. 1994; May et al. 2004). Grain plumpness is a desirable quality parameter in the milling oat industry. It gives an indication how much an oat sample has larger sized groats with uniform seed size. In contrast, thin oats have irregular sizes which do not make the grade for milling oat. As thin hulled oat is found to weigh less than thick hulled oat this results in a higher test weight. Thin oat (<0.8mm width) have a high hull percentage, which makes them less desirable for milling oat.

Nitrogen response may vary between oat cultivars (Ohm 1976, Frey 1959, May et al. 2004). May et al. (2004) reported a nitrogen-by-cultivar interaction for grain yield. The yield of

CDC Pacer increased at a quadratic rate with increased nitrogen, while the yield of AC Assiniboia increased linearly.

A challenge faced by the oat grower is achieving standability with high yield capacity. Lodging is in many cases is the limiting factor in achieving maximum yield by increased nitrogen supply. Lodging is the permanent displacement of stems from an upright position (Berry et al. 2007), usually occurring after the panicle has emerged and results in the shoots leaning or lying on the ground. Lodging takes several forms ranging from the bending of the stem, breaking of the stem and also the failure of the root system to support the plant It is a complicated phenomenon influenced by many factors including: cultivar, rain, wind, topography, soil type, and disease (Berry et al. 2007). It is most often associated with conditions that promote plant growth such as an abundant supply of nutrients and adequate moisture. Often, lodging occurs in oat when growers attempt to maximize yield through high rates of nitrogen fertilization, and the resultant growth makes the crop more susceptible to lodging. The effect of nitrogen fertilizer on oat lodging has been well investigated. Mohr et al. (2007) reported increasing nitrogen rates resulted in increased lodging score even though the cultivar grown was deemed to have very good lodging resistance. Similar findings have been reported in previous research where Mulder (1954), observed an increase in lodging when 110 kg $ha^{-1}$ of nitrogen had been applied. Plants supplied with higher rates of nitrogen were found to have longer lower culm internodes than those grown with low nitrogen supply. At the onset of anthesis the effects of lodging are severe, yield declines by more than 1% for every day that the crop remains lodged (Stapper and Fisher 1990). Lodging that occurs after the plant matures may not affect the yield but it may reduce the amount of harvestable grain. Two major types of lodging occur in oat: stem and root lodging. Stem lodging is typically caused by one of the bottom two internodes buckling (Neenan and

Spencer-Smith, 1975) and results in the upper stem and ear lying horizontally. Whereas root lodging occurs when the base of the plant fails to anchor with culms leaning from the crown, involving some disturbance of the root system. The effect of root lodging can reduce crop yield by up to 80%, with further losses in grain quality, greater drying costs and an increase in time taken for harvesting. (Berry et al. 2004). Later lodging during early grain filling stage can affect grain quality by reducing thousand kernel weights, test weight, and increasing the protein content (Berry et al. 2004). Lodging after this developmental stage caused smaller effects on quality.

Lodging is cultivar dependent; a tall, weak-stemmed oat cultivar has a greater tendency to lodge than a semi-dwarf cultivar with stiffer straw with abundant supply of soil nutrients and moisture. The mechanisms by which lodging reduces the yield of cereals have been reviewed by Setter et al. (1997), these include reduced translocation of mineral nutrients and carbon for grain filling, increased respiration within the canopy, rapid chlorosis and higher susceptibility to pests and diseases. Small grains and low TKW indicate that lodging reduced the supply of assimilates to the grains; this increases concentration protein. Similar effects on grain size, test weight and protein content was observed in oats in an experiment conducted by Mulder (1954). Lodging can reduce cereal yield by reducing the grain size and number and amount of harvestable crop recovered by the combine harvester (Berry et al. 2007). Plant growth regulators are exogenously applied chemicals that alter plant metabolism, cell division, cell enlargement, growth and development through the regulation of plant hormones (Rajala, 2008). Plant growth regulators refer to any synthetic compound which is used to reduce shoot length of a plant in a desirable way without being phytotoxic (Rademacher, 2000). Plant growth retardants are antagonistic to gibberellins (GA’s) or auxins, the plant growth hormones primarily responsible for shoot elongation. In high input cereal management plant growth regulators, mainly anti-gibberellins have been a cost-effective method in shortening stem length, improving harvestability and consequently increasing lodging resistance (Berry et al. 2004). Generally, PGRs can be classified into two main groups namely; inhibitors of GA biosynthesis and ethylene-releasing compounds. The most commonly used inhibitors of gibberellic acid biosynthesis in cereal crops are chlormequat chloride, mepiquat chloride and trinexapac-ethyl. PGR induced reduction in stem elongation can be attributed to a decrease in gibberellic acid (GA) or an increase in ethylene synthesis (Gianfagna, 1995). This occurs as a result of anti-gibberellic PGR's inhibiting GA biosynthesis at different stages of the metabolic pathway. Trinexapac-ethyl (ethyl-(3-oxido-4-cyclopropionyl-5-oxo) oxo-3-cyclohexenecarboxylate) and chlormequat chloride (CCC, chlomequat (2 chloro-ethyl)-trimethylammonium) are types of anti-gibberellins that reduce stem length by inhibiting natural GA biosynthesis that occurs during stem elongation (Rademacher 2000). Chlormequat chloride has a long residual activity but a long commencement of activity. Conversely, trinexapac-ethyl has a short residual activity but a more rapid start of activity.

Stem length is a major factor associated with lodging sensitivity in cereals (Crook and Ennos 1995, Berry et al. 2000). Abundant nitrogen fertilization, coupled with high moisture facilitates stem elongation and hence, results in lodging susceptibility (Pinthus 1974, Berry et al. 2000). Stem shortening is best achieved when a PGR is applied during early stem elongation phase (Luckwill 1981, Rademacher et al. 1992, Rademacher, 2000). Plant height reduction is related to the reduced elongation of internodes (Peltonen-Saino and Rajala 2001). The peduncle and uppermost internodes are shortened, resulting in reduced shoot leverage which consequentially results in reduced lodging susceptibility (Berry et al. 2000). Substantial stem shortening was observed in oat following treatment with chlormequat chloride, trinexapac-ethyl and ethephon (Clark and Fedak 1977; Rajala and Peltonen-Saino et al. 2002; White et al. 2003). Yield reduction may be attributed to the timing of application and interaction between PGR and cultivar. PGR applications may induce considerable yield reductions in oat, especially when there is no lodging (Cox and Otis 1989, Rajala and Peltonen-Sainio, 2002). There have been reports of yield response in oat following treatments with chlormequat chloride and ethephon on six dwarf oat lines (Peltonen-Sainio and Rajala 2001). The treatment with CCC increased grain yield by 0% -13% depending on the cultivar and year. Ethephon decreased grain yield by up to 17% compared with the control. Cytokinin applications at the flag leaf stage coincide with the onset of floret abortion to fertilization (Peltonen-Sainio and Peltonen 1995).

## 1.2. Research objectives

### 1.2.1. Determine the effect of oat cultivar and nitrogen fertilization on yield and quality

Studies in eastern Canada have shown a nitrogen response in oat cultivars with higher yields associated with higher nitrogen fertilizer rates. In addition, nitrogen fertilizer applications have been shown to increase crop lodging score, with significant negative effects on grain quality.

This research objective will be investigated in Chapter three and the following hypotheses were tested:

- Yield response to nitrogen fertilizer will vary among the five oat cultivars.
- Lodging response to nitrogen fertilizer will vary among the five oat cultivars.
- Cultivars will vary in β-glucan content.

### 1.2.2. Determine the effect of plant growth regulator application and nitrogen fertilization on oat yield and lodging

Research on PGR’s has been primarily conducted in Europe where winter cereals are common and environmental and agronomic conditions differ from western Canada. Determining the influence of plant growth regulators on oat yield and lodging is discussed in Chapter four and the following hypotheses were tested:

- Oat yield and height will differ at different PGR rates
- There will be height reductions following treatment with PGR.
- PGR treatment will result in reduced lodging score in oat.
- The effect of PGR application on oat yield, height and lodging will depend on available soil moisture.

# Chapter Two: Literature Review

## 2.1. Oat production

Oat production ranks sixth in world grain production, next to wheat, rice, barley, corn, and rye (FAOSTAT, 2015). In many parts of the world oat is grown as grain, forage, fodder, straw for bedding, hay and silage. Livestock feed grain is the predominant use of the oat crop, accounting for an average of 74% of the world's total usage in 1995 to 2005 (USDA, 2008). Russia, Canada, the United States, the European Union (EU), and Australia account for 77% of the world's supply of oats (FAOSTAT, 2013). As indicated in Table 2-1, the EU and Russia are the largest producers of oats in the world. In the last decade, the annual average production was around 23 million tons per year, this represents half of the production in the 1960's. Canada is the second largest global commercial producer and exporter of oats, accounting for 15% of total global production and roughly 60% of global exports (USDA, 2017). Figure 2.1 shows oat production for the three Prairie provinces from 1990 to 2014. Alberta was historically the largest grower of oats in western Canada until 1994-95, when Saskatchewan acreage increased. Currently, Alberta has comparable production levels to Manitoba and Saskatchewan is now the leader in oat production. Canada's oat production has a steady-to-high production trend due to the close proximity to the U.S. oat milling market. Oats are well adapted to variable soil types and can perform better on acid soils than other small grain cereals crops. Oats are grown predominantly in cool and moist climates; they can be sensitive to water deficit and heat during head emergence and maturity (Murphy and Hoffman, 1992).

## 2.2. Biology and Morphology

*Avena* belongs to the *Gramineae* family. The primary domesticated species of oat is *Avena sativa*, however *Avena byzantina* and *Avena strigosa* are also grown in some regions for animal feed and fodder. Oat is an annual grass about 1.5 meters high with flat leaf blades; inflorescence shape is open, contracted, effused or one-sided panicles with peduncles of pedicellate spikelets (Ladizinsky, 2012). Oats differ from other commonly grown small grains, possessing an inflorescence in the form of a panicle, while the inflorescences of wheat, barley, and rye are spikes. The growth of the oat plant is favored by relatively cool and moist growing conditions and is influenced by soil physical properties such as soil texture, structure and bulk density as well as available moisture, temperature and solar irradiation (Marshall et al. 1992). The major developmental stages in oat are germination, leaf production, tiller production, stem elongation, panicle development and emergence, anthesis, grain filling and ripening (Zadoks et al. 1974). When the oat seed germinates, starch reserves in the seed provide energy for root and leaf development until the plant begins to photosynthesize. Leaves develop at regular intervals until panicle emergence. In oat, the growth period from planting to anthesis is grouped into vegetative and reproduction phases. During the vegetative phase, after germination and emergence, the plant remains short, internodes are not elongated, leaves are initiated and tillers are formed (Ross, 1955). During the reproductive phase, floral initiation and differentiation occurs. The inflorescence is produced, internodes are elongated and an observable height increase occurs. Tillers emanate in the axils of the foliage leaves between emergence and stem elongation. Tillers that survive till anthesis will produce an inflorescence or panicle. The number of tillers formed depends on density of seeding, cultivar and growing conditions, fewer tillers are formed when seeding density is high or conditions are poor. The inflorescence of oat is in the form of a loose open panicle, with spikelets at the ends of the branches (Gates and Dobraszczyk, 2008). As the seed matures, the plant begins to lose moisture and senesces. The mature oat grain consists of a groat or caryopsis tightly covered by a hull. The hull represents 30–40% of the total grain weight. It is composed of cellulose, hemicellulose, and lignin (Zwer, 2016). Compared with other cereals, the oat groat is slender and covered with hairs under the hull.

## 2.3. Factors affecting oat grain yield

The number of spikelets per panicle, the number of panicles per square meter, and the weight and number of kernels per spikelet are the components that determine oat yield potential. These components determine the sink size, which is formed during the pre-anthesis development period. Sink size refers to the number of grains per ear whereas the availability of assimilates to fill these grains is the source. The number of panicles $m^{-2}$ has been reported to increase with nitrogen fertilization (Maral et al. 2013), with 536 panicles $m^{-2}$ being obtained from 200 kg $ha^{-1}$ nitrogen rate. This confirms a study conducted by (Browne et al. 2006), indicating an increase in panicle number $m^{-2}$ with nitrogen fertilization. Root, leaf, stem and tiller production, control of phasic development and panicle structure and development are the pre-anthesis processes affected by dry matter accumulation of and partitioning (Brouwer and Flood, 1995). Potential kernel sizes and yield output is determined by tiller initiation and survival, as well as panicle differentiation (Shanahan et al. 1984). Each tiller has the potential to produce a grain head.

Tillering can be advantageous, as it may be correlated to high yielding ability, or disadvantageous as secondary tillers may produce little grain of poor quality due to completion for photosynthetic material and nutrients. Therefore, early growing conditions are essential determinant of growth in oat. Tillering persistence is the determinant of one important yield component, namely panicle number (Deiss et al. 2014). The growth, production and survival of tillers depends on growing conditions; only a fraction of tillers may survive to produce panicles contributing to yield. Larger and older tillers have a high survival rate in comparison to smaller and young ones, basal tillers survived better and were more productive than tillers originating from third leaf (Wiggans and Frey, 1957). Numerous researchers have attempted to quantify the contribution of tillers to yield as well as the relationship between the two. Anderson (1986) reported a positive association between tiller production and grain yield in wheat ($R^2 = 0.45$) with up to 600 tillers per square meter. Peltonen and Peltonen-Saino (1997) found that in a favorable year tillers contributed 13-23% to groat yield, whereas under poor post-anthesis conditions tillers underwent senescence and contributed 6% to final yield. In an experiment conducted by Makela et al. (1996) to evaluate the contribution of tillers to grain yield, a range of oat cultivars were assessed using nitrogen fertilizer rates of 0, 80 and 120 kg $ha^{-1}$. The results indicated nitrogen did not affect the number of tillers per main shoot and therefore did not significantly affect tiller contribution to grain yield.

Increasing nitrogen fertilizer asymptotically increases yield (Brunner and Freed 1994). Various experiments have proved that oats will respond to applied fertilizer when soil N is limiting. Nitrogen fertilizer application has been shown to significantly increase oat grain yield. May et al. (2004) reported a significant increase of oat grain yield in response to nitrogen fertilizer treatment, with results indicating a yield increase with fertilizer rates of 40 to 80 kg $ha^{-1}$ N and a decline at higher nitrogen rates. In a further study conducted in Manitoba at 6 site-years to investigate the effect of N, P and K on oat yield and quality, Mohr et al. (2007) concluded that plant-available nitrogen supply of 100 kg $ha^{-1}$ N was adequate to achieve optimum grain yield. This suggests a higher rate of nitrogen fertilizer was not required to optimize grain yield under conditions of higher yield potential. Additional nitrogen inputs above this level did not result in further yield increases and resulted in deterioration in physical grain quality and increased susceptibility to lodging. Phosphorus application increased yield in 2 of 6 site-years, without a significant effect on quality. The application of 33 kg $ha^{-1}$ potassium as KCl resulted in a marginal but statistically significant increase in grain yield, equivalent to a 2.2% increase averaged across all site-years.

Cultivar is a key determinant of yield, and when sufficiently supplied with moisture, have been shown to respond differently to nitrogen fertilization. Low to moderate nitrogen rates significantly increased yield, with optimum relative yield achieved in AC Assiniboia oat with plant available nitrogen supply of approximately 100 kg $ha^{-1}$ (Mohr et al. 2007). Brinkman and Rho (1984) reported a grain yield response to N with the tendency for Stout oat to produce higher grain yields than Lodi and Marathon at the higher rates of N. This pattern was apparent in each of the environments. Stout's larger grain yield response to N occurred primarily between 28 and 84 kg $ha^{-1}$. May et al. (2004) reported oat cultivars CDC Pacer and AC Assiniboia responded differently to increasing nitrogen rates. As the rate of applied nitrogen rate increased, the yield of CDC Pacer increased quadratically, while the yield of AC Assiniboia increased linearly suggesting that varieties have different ability to respond to increases in nitrogen fertility.

Lastly, considerable factors that may also affect grain yield include soil moisture, soil supply of nutrients, disease and temperature.

### 2.3.1. Agronomic management and characteristics of oat

Oat can be grown under less than ideal production conditions, and is thus considered one the most adaptable cereals suited to almost any soil type as long as moisture and temperature are suitable (Sorrells and Simmons, 1992). Good agronomic management practices are essential to realize the genetic potential of oat cultivars. Some good management practices consist of sowing certified seed and use optimum seeding and fertilizer rates, seed treatment and selection of fields with low weed pressure. Cultivar selection should be based on maturity, lodging and disease ratings. Adequate soil and plant nutrition is essential to achieve maximum yields, inputs such as nitrogen, phosphorus, potassium, and sulfur fertilizers should be applied based on soil test recommendations. Other agronomic management practices that affect oat yield and quality include seed treatments and fungicide applications. According to Mourtzinis et al. (2015), the use of Headline foliar fungicide resulted in an average yield increase of 838 kg $ha^{-1}$ across varieties compared to the non-treated oat yield.

### 2.4. Lodging in oat

A challenge confronting the oat grower is avoiding lodging while achieving high yield. Lodging is a dominant limiting factor on grain production causing reductions in grain yield and quality (Berry,1998). Often, lodging occurs in oat when growers attempt to maximize yield through high nitrogen fertilization, the resultant growth make the crop more susceptible to lodging. Lodging in oat can negatively affect yield and quality through the interruption of the grain filling process. The mechanisms by which lodging reduces the yield of cereals include reduced translocation of mineral nutrients and carbon for grain filling, increased respiration within the canopy, rapid chlorosis and higher susceptibility to pests and diseases (Setter, 1997). Lodging is an intricate phenomenon influenced by many factors including cultivar, rain, wind, topography, soil type, and disease (Berry et al. 2007).  It is associated with conditions that promote plant growth such as an abundant supply of nutrients and adequate moisture. Lodging can hinder harvest by from slowing harvest operation through to yield loss when lodging is severe. Also, lodging can reduce grain yield by reducing the grain number and the amount of harvestable crop recovered by the combine harvester (Berry et al. 2007).

Two forms of lodging are identified in literature. Stem lodging occurs when the stem is displaced from an upright position to lying flat on the ground. It is typically caused by one of the bottom two internodes buckling (Neenan and Spencer-Smith, 1975) resulting in the upper stem and ear lying horizontally. Root lodging causes root-soil system failure (Ennos, 1991). Root lodging occurs when the base of the plant fails to anchor in with culms leaning from the crown, involving some disturbance of the root system. Crops which lodge before anthesis often have smaller yield losses than crops that lodge soon after anthesis (Fischer and Stapper, 1987).

Some studies have been carried out to measure the effect of lodging on oat yield. Severe lodging of oat occurred 25 days after anthesis (Burrows, 1986). Yield reductions from lodging has been reported to reduce yields of oat up to 37% (Pendleton 1954).

The effect of nitrogen fertilizer on the lodging of oat has been investigated. Ohm (1976) reported a significant difference in nitrogen fertilizer treatments for lodging score in 21 oat cultivars. Two nitrogen treatments: one, no added nitrogen fertilizer with 40 to 50 kg $ha^{-1}$ available in the soil, and two, 110 kg $ha^{-1}$ applied in a split application. Application of nitrogen fertilizer increased lodging score of all cultivars. However, the lodging scores of weaker strawed cultivars (Clintford and PG1353-1) did not always increase more with N application than those of stronger strawed cultivars (Diana and Allen). Pendleton (1954) conducted an experiment where oat plots were artificially lodged at two dates, 4 and 20 days after heading respectively. Two angles of lodged plots, 45° and 90° (flat) were compared to upright plots. Lodging was achieved by placing a 0.05 meter squared wooden stake into the ground at the end of the oat rows and stretching a twine between to achieve the desired angle of lodging. Average yield of early lodged plots was 388 kg $ha^{-1}$ less than the yield of late lodged plots and 648 kg $ha^{-1}$ less than upright plots. Plants lodged at 90° compared to 45° yielded 598 kg $ha^{-1}$ less at the first lodging date and 373 kg $ha^{-1}$ at the later date.

### 2.5. Genetic and environmental variation of grain yield in oat

Yield potential is dependent on genotype, environment and their interaction (Evans and Fischer, 1999). Biological elements such as mineral uptake, photosynthetic capacity, disease resistance and leaf area are controlled by an exclusive combination of genes assembled in the cultivar being grown (Forsberg and Reeves, 1995). Climatic condition is a major environmental factor which may limit or enhance the realization of a cultivar's yield potential (Peltonen-Sainio, 1991). Available moisture and temperature are among the most important climatic factors; moist and cool climates are favorable conditions under which the oat crop best thrives (Forsberg and Reeves, 1995). Water shortage can cause severe loss of the grain yield of oat (Sandhu and Horton, 1977). In order to produce high grain yield in oat, there must be an optimum supply of moisture during the entire vegetation period (Rodionova et al. 1994). Experiments conducted in Latvia showed that higher oat yields were obtained when there was abundant rainfall during the vegetation period (Zute and Gruntiņa, 2002). Drought conditions tend to decrease the number of panicles per plant and florets per panicle associated with floret sterility (Sandhu and Horton, 1977). The yield of an oat cultivar is closely linked with average daily temperature during periods of seedling growth to anthesis. Higher air temperatures result in lower grain yield (Zute and Gruntiņa, 2002). Optimal temperatures required for oat to produce high grain and straw yields is approximately 13°C to 19°C (Sorrels and Simons, 1992). Tamm (2003) reported that both cultivar genotype and climatic conditions had significant effects on the grain yield of oat. A three-year field experiment was conducted in Estonia from 1998 to 2002 with 101 oat cultivars from Canada, USA, Sweden, Russia, Germany and Russia. The Estonian cultivar “Jaak” was used as a check. Variation in grain yield of cultivars was estimated by calculating averages, coefficients of variation as well as maximum and minimum values. Average grain yield of oat cultivars varied from 3,288 to 5,824 kg $ha^{-1}$. Lowest average grain yield was recorded in 1999 when high temperature and extreme drought conditions inhibited the development of oat starting from heading while average grain yield was highest (5824 kg $ha^{-1}$) in 2000. Relatively low average level of grain yield of 3,531 kg $ha^{-1}$ was caused by heavy lodging at the time of heading.

### 2.6. Nitrogen-cultivar interactions

The effect of nitrogen fertilization can vary due to environmental factors such as soil conditions, climate, especially rainfall and genotype. Maral et al. (2013) conducted field experiments in 2007 to 2009 growing years to examine the response of six oat cultivars (Seydisehir, Apak, Yesilkoy-330, Amasya, Checota and Yesilkoy-1779) to three nitrogen rates (0, 100 and 200 kg $ha^{-1}$) for agronomical traits. Traits measured included panicle number per $m^{-2}$, plant height, 1000-grain weight, grain yield and harvest index. Among the cultivars, the differences for investigated traits were significant. As average of two years, the highest grain yield (2590 kg $ha^{-1}$) was obtained from Checota cultivar. Grain yields of Yesilkoy-330 (2480 kg $ha^{-1}$) and Yesilkoy-1779 (2440 kg $ha^{-1}$) cultivars were also higher than the others and those cultivars were placed in the same group with Checota cultivar. The Checota, Yesilkoy-330 and Yesilkoy-1779 cultivars when compared to the average yield of the other cultivars provided a higher grain yield at the rate of 26.7%, 21.2% and 19.1%, respectively. Results of the two-year average indicated the lowest grain yield (2000 kg $ha^{-1}$) was obtained from Amasya cultivar. Seydisehir (2050 kg $ha^{-1}$) and Apak (2080 kg $ha^{-1}$) cultivars also were placed in the same group with Amasya cultivar.

Differences in yield among the cultivars grown in the same environment were due to genetic differences. When compared to control level (0 kg $ha^{-1}$), nitrogen rates of (100 and 200 kg $ha^{-1}$) significantly increased all the preceding investigated traits. Grain yield at the level of 100 and 200 kg $ha^{-1}$ was increased by 34.6% and 63.2%, respectively compared to control level 0 kg $ha^{-1}$. Muurinen et al. (2007) reported similar results indicating an increase in grain yield due to increased nitrogen application rates. Cultivar – nitrogen interactions imply that oat cultivars would differ in their response to N. Therefore, some cultivars would be more responsive than other cultivars to the addition N. Some studies have reported that the grain yield of some oat cultivars were more responsive than other cultivars to the addition of N (Frey 1959; Brown et al. 1961). Although these studies did not use rates of N high enough to observe a yield decrease from further application of N, Brinkman and Rho (1984) used N levels that were high enough to reduce grain yield. They found that the yield of three oat cultivars was depressed by high N rates, but the optimum N fertilizer rate was 56 kg ha–1 for one cultivar and 84 kg ha–1 for the other two cultivars.

Plant height response to nitrogen fertilizer has been observed in oat cultivars. This response to nitrogen fertilizer is generally recognized. The application of nitrogen fertilizer resulted in significant increases in plant height among 21 oat cultivars (Ohm 1976), with all cultivars producing taller straw with nitrogen fertilizer additions. Maral et al. (2013) reported a 6% increase in average plant height when nitrogen fertilizer application increased from 0 kg $ha^{-1}$ to 200 kg $ha^{-1}$.

Adequate nitrogen fertilizer use is an essential component to cost-effective crop production and sustainable agriculture in Western Canada as nitrogen is the most frequent limiting nutrient in crop production (Tisdale et al. 1993). Nutrient deficits in oat, during the first half of the growing season will lead to less vigorous plants with smaller leaves and panicles and less developed root systems (Forsberg and Reeves, 1995). Nutrient deficiencies, which occur during the latter part of the growing season, will negatively affect seed set and grain filling (Forsberg and Reeves, 1995). Humpherys et al. (1994) reported that nitrogen fertilizer application at seeding and booting stage of plant development caused changes in the protein and oil content of four oat cultivars studied in Quebec Canada. Nitrogen fertilizer tended to increase protein content and to decrease oil content.

### 2.7. Plant growth regulators in oat production

A plant growth regulator (PGR) refers to any synthetic compound that affects plant growth and development by altering the level of growth hormones within the plant. Plant growth retardants are a group of plant growth regulators which are used to reduce the shoot length of plants while maintaining developmental patterns. In this thesis, the term PGR is used in a prescribed manner to denote exogenously applied chemicals, primarily targeted to shortening stem length, generally referred to as anti-lodging agents. In high input cereal management, PGRs have been used to shorten stems and reduce lodging susceptibility (Gianfagna, 1995; Rajala and Peltonen-Sainio, 2000). Environmental conditions can increase the occurrence of lodging, notably high winds, increased rainfall, variation in soil conditions as well as increased available nitrogen (Berry et al. 2003). Grain lodging is an intricate phenomenon resulting from innate factors such as genotype, soil characteristics, climatic conditions and cultural practices. Genotypic factors such as cellulose content, hemicellulose and lignin, specifically in the basal internodes, and plant height are characteristics strongly associated with resistance or susceptibility to lodging (Zhu et al. 2004). Lodging that occurs at pre-anthesis or during early grain filling can cause considerable yield loss by interrupting nutrient and photosynthate transport and translocation, interference with light absorption of the canopy and intra-plant water availability. Additionally, lodging increases time and energy needed for combine harvesting and drying. These ultimately cause an increase in production costs. Hence, reducing lodging in cereals promotes quantity, quality and harvestability of the grain and helps ensure an acceptable economic outcome (Rajala and Peltonen-Sainio, 2000). Anti-gibberellic PGRs are antagonistic to gibberellins (GA's) and are primarily used for shortening cereal stems by inhibiting GA biosynthesis at different stages of the metabolic pathway (Rademacher, 2000). Gibberellins are a large group of endogenously synthesized plant hormones that trigger stem lengthening through enhancing cell elongation (Goodwin and Mercer, 1983). This review discusses the GA biosynthesis pathway, mode of action of growth retardants and the effect of PGRs on oat yield and lodging. Plant growth regulated induced reduction in shoot length can be attributed to reduction of GA or inhibition of the GA biosynthetic pathway (Gianfagna, 1995). The GA biosynthesis pathway encompasses four main phases. The first phase is a pathway from mevalonic acid or D-glyceraldehyde 3-phosphate to geranylgeranyl pyrophosphate (GGPP), the second phase is the cyclization of GGPP to *ent*-kaurene, the third phase involves conversion of *ent*-kaurene to $GA_{12}$-aldehyde, and lastly the conversion of $GA_{12}$-aldehyde to other GAs (Lichtenthaler, 1999; Rademacher, 2000). Different antigibberellins block the GA biosynthesis pathway at different stages (Figure 2.2). Onium-type compounds such as chlormequat chloride (CCC) and mepiquat chloride interfere with the early stages of GA biosynthesis primarily by blocking the A-activity of *ent*-kaurene synthesis (Böse et al. 1992; Rademacher, 2000). PGRs such as cyclohexanetriones, including trinexapac-ethyl, interfere with GA biosynthesis in the late stages of the metabolic pathway, by inhibiting 3ß-hydroxylation of $GA_{20}$ to active $G_{A1}$ (Adams et al. 1992; Rademacher, 2000).

Reduction in stem elongation following PGR application can be linked closely to reduced GA synthesis. One of the major factors associated with lodging sensitivity is stem length (Crook and Ennos, 1995; Berry et al. 2000). Furthermore, stem elongation is aided by high latitudes, long days and a low angle of incident radiation (Salisbury, 1985). An effective way of reducing the risk of lodging in oat is through shortening the stem through the application of a PGR. In order to achieve this objective, PGRs are applied at early stem elongation phases (Rademacher et al. 1992) or at advanced growth stages; the latest at booting stage (ethephon, trinexapac-ethyl, Luckwill, 1981; Rademacher et al. 1992). Plant height is reduced as a consequence of PGR treatment shortening the elongation of internodes (Crook and Ennos, 1995; Peltonen-Sainio and Rajala, 2001). As a result, the uppermost internodes and peduncle are shortened. Rajala and Peltonen-Sainio (2002), reported a reduction in shoot elongation in oat when measured 14 days after treatment with trinexapac-ethyl. However, there was no PGR by cultivar interaction in this study, suggesting all cultivars responded similarly. Effective stem length reduction was observed when PGRs was applied at the recommended time, chlormequat chloride at GS 31-32, trinexapac-ethyl and etephon at the flag leaf stage GS 39-40

. In this study, there was a strong interaction between year and PGR treatment.

Generally, PGR applications are not approved for plant stands suffering from or expected to be exposed to drought or other abiotic stresses. This is to avert potential PGR induced stress which consequently has detrimental effects on seed yield. Physiological stress in cereals, caused by PGR application, has been studied to an extent (Rademacher, 2000). PGR applications, especially ethephon have been documented to cause yield reduction (Simmons et al. 1988).

Further research suggests PGRs applied as a seed treatment or at early growth stages may improve the tolerance cereals to abiotic stresses. Seed treatment with paclobutrazol improved drought, heat and waterlogging tolerance of wheat seedlings (Gilley and Fletcher, 1997). Chlormequat chloride enhanced growth and yield performance of wheat when applied as seed dressing under dry conditions (De et al. 1982).

In an attempt to minimize the occurrence of lodging in cereals, there have been reports of the use of growth regulators such trinexapac-ethyl in wheat (Berti et al. 2007) and rice (Arf et al. 2012). In terms of yield response, there is limited information regarding PGR treated oat experiments in western Canada. Yield responses to PGR treatments have been inconsistent; PGR's have been reported to have negative, positive or have no effect on yield. (Rajala and Peltonen-Sainio, 2002). This outcome seems to be typical of PGR experiments (Simmons et al. 1988; Pietola et al. 1999; Peltonen-Sainio and Rajala, 2001). In evaluating the effect of trinexapac-ethyl growth regulator concentration on grain yield, plant height and lodging, Hawerroth et al. (2015) reported that high rates of trinexapac-ethyl application had no negative impact on grain yield of oat. Also the PGR reduced plant height and percent lodging of oat. The experiments were conducted in 2010, 2011 and 2012 under different cultivation environments in Brazil. In each environment four trinexapac-ethyl (0, 50, 100 and 150 g.a.i $ha^{-1}$) and two nitrogen treatments (30 and 90 kg $ha^{-1}$) were applied, respectively. An increase in trinexapac-ethyl concentration resulted in a trend toward a linear reduction in plant height in wheat (Berti et al. 2007). A field experiment was conducted by Rajala and Peltonen-Sainio (2002) to evaluate the response of tiller growth and productivity to chlormequat chloride, trinexapac-ethyl and ethephon in oat, wheat and barley. Application of chlormequat chloride at growth stage 13-14 increased grain yield in oat by 7% and ethephon applied at growth stage 39-40 decreased it by 5%. Trinexapac-ethyl treatment had no significant effect on oat grain yield. Neither PGR cultivar nor PGR cultivar  year interactions occurred for grain yield in oat. Laverick (1997), conducted experiments to determine the effect of PGR application on oat yield with naked oat cultivars. Significant responses to PGR application were not obtained across all eight sites; however, yield increases of up to 1.56 tons per hectare was measured in one experiment. Peltonen-Sainio and Peltonen (1997) reported an increase in grains per panicle of chlormequat chloride treated oat compared to control plants, when the possibility of manipulating tiller growth with early chemical applications on oat cultivars at different seeding rates was assessed. Further research conducted by Browne et al. (2003) to investigate the effects of nitrogen, seed rate and chlormequat chloride on grain yield and quality contrastingly indicated oat yields were not significantly affected by chlormequat chloride application but increased at higher rates of nitrogen and seed rate. The use of a PGR may prove to be a beneficial agronomic tool if it is able to maintain yield, enhance grain quality and facilitate harvesting.

## 2.8 Oat grain β-glucan content

β-glucans are natural polymers made up of glucose molecules linked together by a series of beta-(1, 3) and (1, 4) linkages, comprising a class of non-digestible polysaccharides called β-D-glucans (Daou and Zhang, 2012). In oat grains β-glucan is found primarily in the endosperm and the subaleurone layer (Wood, 1993). β-glucan has been identified as a component that can lower blood serum cholesterol (Davidson et al. 1991). Oat β-glucan has strong cholesterol and triglyceride lowering properties leading to reduced cardiovascular diseases (Daou and Zhang, 2012). Anderson et al (1991) demonstrated that oat bran contained β-glucan and reduced total blood serum cholesterol in hypercholesterolemic subjects by as much as 23% without a change in high-density lipoprotein cholesterol.

It is critical to investigate the influence of genetic and agronomic factors on grain oat β-glucan content in order to increase β-glucan content of commercial oat production. A major agronomic factor which may influence grain β-glucan content and other traits in oat is available soil nitrogen (Brunner and Freed, 1994). Significant differences in β-glucan content among oat cultivars have also been reported (Peterson, 1991; Welch et al. 1991).

A field experiment conducted by Peterson (1991) in which twelve oat cultivars were grown at nine different locations to investigate the level and distinctiveness in β-glucan concentration. Significant differences were found for the main effects of cultivar and location and their interaction. Comparable findings have been reported by Saastamoinen et al. (2008) in an oat cultivar trial conducted to evaluate the effect of cultivar, location and year on β-glucan of six oats cultivars at ten locations in Finland. Significant differences were found between cultivars and location for β-glucan content. In a controlled greenhouse experiment with six oat cultivars, Welch et al. (1991) observed a significant increase in β-glucan content for high nitrogen versus low fertility treatments. This is in contrasts to (Brunner and Freed, 1994), who found no significant differences in mean β-glucan concentration between locations or among cultivars. However, he reported a non-significant β-glucan content increase at higher levels of applied nitrogen. Similar results have been published by Humphreys et al. (1994) who reported nitrogen fertilization has no effect on β-glucan content of oat.

**Table 2-1** Top ten oats producers in 2013 (Thousand metric tons).

| | |
|---|---|
| European Union | 7,581 |
| Russia | 4,027 |
| Canada | 2,680 |
| Australia | 1,050 |
| United States | 929 |
| Ukraine | 630 |
| Belarus | 600 |
| China | 580 |
| Chile | 560 |
| Argentina | 400 |
| World Total | 20,732 |

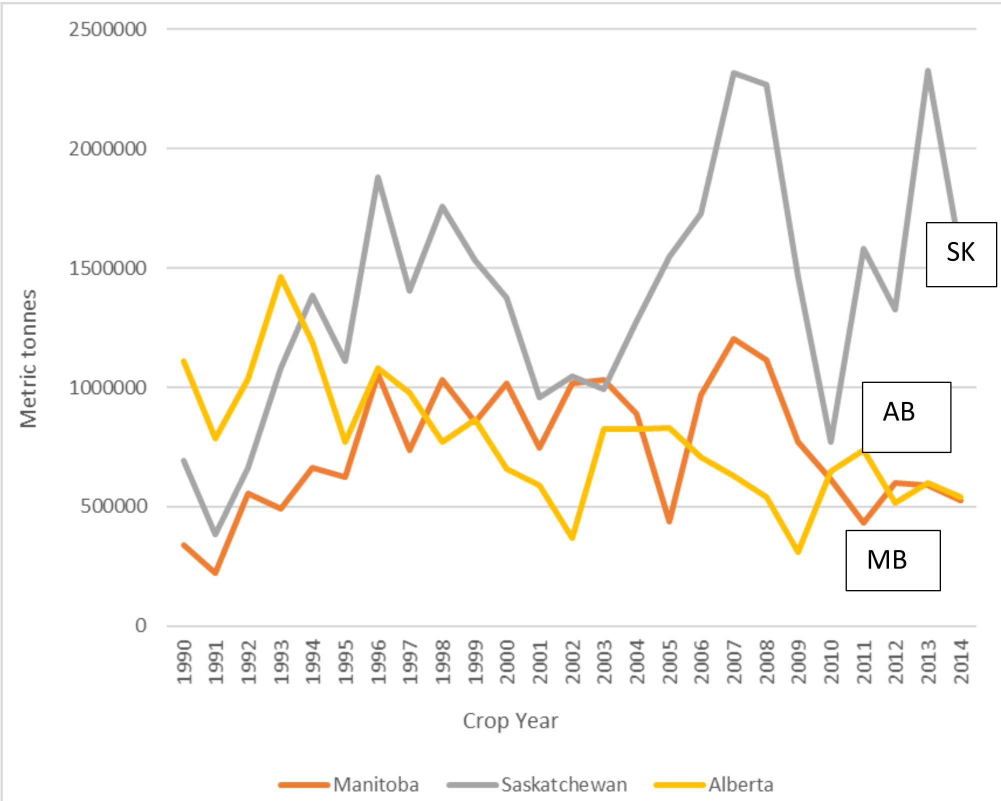
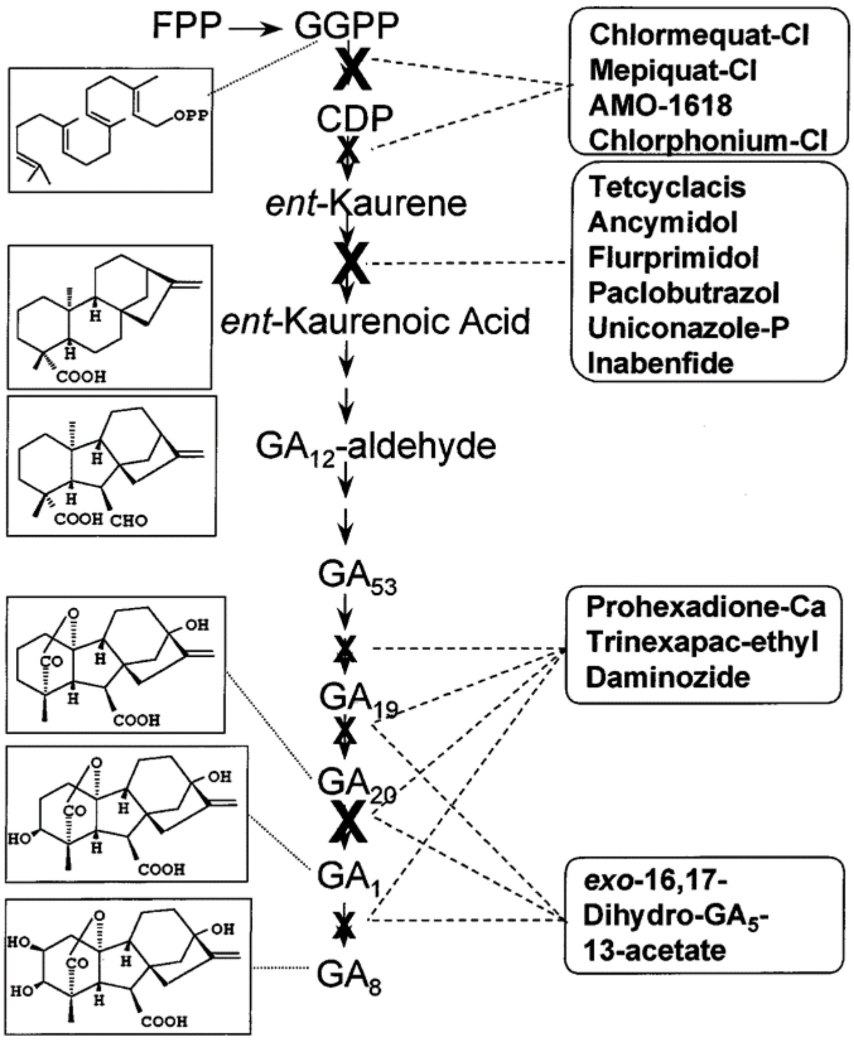



**Figure 2-1.** Estimated production of oat in the prairie provinces, in metric units, annual, Statistics Canada. CANSIM (database). (February 11, 2017).




Abbreviation: FPP = Farenosyl pyrophosphate, GGPP = Geranylgeranyl diphosphate.

**Figure 2-2.** Simplified illustration of biosynthetic stages involved in GA biosynthesis and points of inhibition by plant growth retardants (X, x = major and minor activity, respectively). Adapted from Rademacher (2000).

# Chapter Three: Effect of oat cultivar and nitrogen fertilization on yield and quality

## 3.1. Introduction

Oat is a high yielding crop suitable for the short growing conditions found in central and northern Alberta. While oat can be sold as animal feed, by meeting milling specifications for plump kernel/percentage of thin seed, high test weight and β-glucan content, growers may be able to sell oat into the milling market which increases its value. Oat is of interest to the milling industry because in Canada and in the United States, foods containing oat bran, rolled oats or whole oat flour that would deliver specified amounts of β-glucans (0.75 g of oat β-glucans per serving) may carry a human disease risk reduction claim stating that they have been shown to lower cholesterol, a risk factor for heart disease (Health Canada 2010). There is a range of quality parameter standards used by oat purchasers ranging from: purchase of particular cultivars; to specified thresholds for quality parameters; or β-glucan content. To the best knowledge of the author, no price premiums are paid for higher β-glucan content although low β-glucan or growing varieties with low β-glucan can preclude sales into the milling oat market. The 10-year average Alberta oat yield is 3000 kg $ha^{-1}$ (Agri-Food Statistics Update, 2014), which is far below the crop's yield potential of approximately 7600 kg $ha^{-1}$ in areas with high rainfall. Alberta's climate is suitable for oat production, but current agronomic practices and cultivar choices have not produced the high quality required for premium prices from millers. Also, a large amount of the feed oats is produced and fed on farm with a small amount moved to the Canadian racehorse market.

Oat cultivar choice for growers is key as it affects yield, lodging resistance and is the primary factor affecting β-glucan content (Saastamoinen et al. 2008). Wang et al. (2016) in an experiment conducted in Scott and Kernen, Saskatchewan; reported a significant cultivar effect on average β-glucan content ranging from 4.2% to 6.1%. No significant effect of growing environment of β-glucan content was observed. These studies contradict an earlier study by Brunner and Freed (1994) who reported oat β-glucan content was mainly influenced by year of cultivation, while cultivar effect was not significant. This could be attributed leaching of the glucose, a precursor of β-glucan, from the flag leaf and awns during severe rainfall events.

While the milling industry focus on oat quality parameters, growers first consider profitability, influenced by both grain quality and price and yield.

When growers choose oat cultivars, yield is the primary consideration, followed by lodging resistance (Yan et al. 2016). In areas of western Canada where rainfall is higher, lodging is a severe problem in many cereal crops, including oats, and may result in lost yield and quality reductions. Lodging at the beginning of the grain filling period has been reported to reduce grain yield in wheat by between 50% and 80% (Stapper and Fischer, 1990; Easson et al. 1993) and in oats by 37% (Pendleton, 1954). These substantial yield losses occur through interference with nutrient and photosynthate transport and translocation (Rajala, 2008). Lodging prolongs and makes harvesting operations trying for the oat grower. In addition to cultivar, wind, rain, soil type and abundant supply of nutrients significantly influences lodging (Berry et al. 2004). Increasing nitrogen fertilizer rates may significantly increase crop yield but also increase lodging and decrease quality parameters (test weight, protein content and kernel plumpness) (Marshall et al. 1987; Jackson et al. 1994). May et al. (2004) reported optimal grain yields were consistently achieved with the application of moderate rates (40 to 80 kg $ha^{-1}$) of nitrogen fertilizer. However, the same authors related plump seed and test weight decreased with increased nitrogen, and varieties CDC Pacer and AC Assiniboia responded differently to increasing nitrogen rates. As the rate of applied nitrogen increased, the yield of CDC Pacer increased quadratically, while the yield of AC Assiniboia increased linearly suggesting that varieties have different ability to respond to increases in nitrogen fertility. Lafond et al. (2013) reported that increasing nitrogen fertilizer significantly increased grain yield but decreased 1000 seed weight, and plumps which increased thin kernels. Higher yield can be negatively correlated with quality parameters and lodging resistance. When making cultivar and production practices decisions, an understanding of the yield potential of cultivars and the tradeoffs between yield, quality parameters and harvestability is necessary to optimize economic return.

A single oat cultivar is grown on 57% of the cultivated oat acres in Alberta (AFSC, 2017). AC Morgan; a white hulled milling oat cultivar has high grain yield and good lodging resistance (Table 3-1), but low β-glucan content can exclude it from some milling markets.

The objective of this study was to investigate the effect of nitrogen fertilizer rates on the yield and quality of five oat cultivars grown in central Alberta. Cultivars were chosen for high potential yield, and a wide range of β-glucan contents and agronomic traits. We were interested to determine if other oat cultivars could yield similar to AC Morgan for Alberta oat growers and allow access to additional milling markets.

## 3.2 Materials and Methods

### 3.2.1. Trial Location and Design

A field experiment was conducted from 2014 to 2016 at two locations in western Canada; Barrhead (54º 06' N, 114º 23' W) and St. Albert (53° 41' N, 113° 37'), Alberta. Environmental data, including monthly accumulated precipitation and average monthly temperature were collected from the nearest weather station to St. Albert and Barrhead (Table 3-2). Soil samples were collected each spring to determine soil chemical and nutrient status (Table 3-3). The experimental design was a randomized complete block design with four replicates. A factorial arrangement of treatments included five oat cultivars (AC Morgan, CDC Morrison, Stride, CDC Norseman and CDC Sea Biscuit) and four N rates (5, 50, 100 and 150 kg $ha^{-1}$ N). Oat was direct seeded into canola stubble in early- to mid-May at a seeding rate of 450 viable seeds $m^{-2}$ into experimental plots that measured 8.5 m by 1.2 m using a Fabro® air seeder equipped with double shoot Atom Jet® hoe openers, in six rows at 20 cm spacing and 2 cm depth at St. Albert and a Fabro® double disc drill with 25 cm row spacing with mid row N fertilizer banding at Barrhead. Nitrogen was applied as urea (46-0-0) at seeding 5 cm below and to the side of the seed. Based on soil analysis, 45 kg $ha^{-1}$ P was applied as monoammonium phosphate, 50 kg $ha^{-1}$ K applied as potassium chloride and 15 kg $ha^{-1}$ S applied as ammonium sulphate at Barrhead; whereas, 27 kg $ha^{-1}$ P was applied as monoammonium phosphate and 29 kg $ha^{-1}$ S applied as ammonium sulphate at St. Albert.

### 3.2.2. Data Collection

Oat stand density was determined 21 days after planting by counting plants in 0.5 m of rows 2 and 3, two meters from the front of the plot, and rows 4 and 5, two meters from the back of each plot. Plant height was measured at maturity for five randomly chosen plants per plot.

Lodging was visually assessed at physiological maturity using a lodging index (1 = upright or 90° to 5 = flat or 0°, relative to the ground) (Wiersma et al. 1986). At maturity, each plot was harvested with a small plot Wintersteiger® combine harvester. Grain samples were dried to constant moisture (13.5%), cleaned and weight recorded. Seed test weight was measured using methodology specified by the Canadian Grain Commission (1998). Percent plump grain was determined by the weight of a 50 g sample that did not pass through a 5.5/64 by ¾ inch slotted sieve, with double oat removed prior to sieving. Percent thin grain was determined by the weight of grain from a 50 g sample that passes through a 5/64 by ¾ inch slotted sieve. The two sizes of sieves were arranged one on top of the other with the larger sieve on top, with the sieve slot vertically facing the same direction and seed sample shaken sideways ten times. The grain remaining on top of the 5.5/64 by ¾ inch slotted sieve was weighed and considered as plump seed, while the grain that fell through the 5/64 by ¾ inch slotted sieve was weighed and considered as thin seed. β-glucan content of cultivars was determined using the mixed-linkage β-glucan assay kit obtained from Megazyme International Ireland Ltd., Wicklow, Ireland) following the McCleary assay procedure (McCleary and Codd, 1991).

**3.2.3. Data analysis**

Data were analyzed with a linear mixed model procedure, Lme4 of R (Bates et al. 2014). Cultivar and nitrogen rate were considered fixed effects. Year and location, replicates within location and year were considered random. The applied treatments considered to be fixed effects to determine the overall effect of fertilizer application on oat. Assumptions of group variances were checked in diagnostic Box-Cox plots before performing analysis of variance. Additionally, the assumption of normality in errors were assessed with normality probability plots. For all variables investigated, LSmeans (Least Square Means) were compared using Turkey's least significant difference test. A regression equation, describing responses to N fertilizer rates was averaged across cultivars for the primary variables of interest in the absence of significant cultivar by nitrogen fertilizer interactions. β-glucan analysis of oat cultivars was carried out at the 100 kg $ha^{-1}$ N rate because preliminary tests showed no N effect on β-glucan. LSmeans of cultivars and statistical differences between cultivars over years were presented.

### 3.3. Results and Discussion

Soil moisture was adequate in all site years, however, in 2015 Barrhead and St. Albert received 48% of the long-term average precipitation between May and August, creating abnormally dry growing conditions. In 2014 Barrhead and St. Albert received 76% and 98% respectively of the long-term average whereas, in 2016 Barrhead and St. Albert received 146% and 110% of the long-term average precipitation respectively (Table 3-2).

Average temperatures throughout the growing season were near normal between locations.

Soil texture was a silty clay at St. Albert (12.6% sand, 43.6% silt, 43.8% clay) to clay loam at Barrhead (75% silt loam, 25% clay loam). Organic matter ranged from 6% at Barrhead to 11% at St. Albert and pH between 5.7 and 8.1. Soil classifications, descriptions and nitrate levels are shown (0-15 cm) for each site-year (Table 3-3). Soil pH and organic matter levels were higher at St. Albert, and lowest at Barrhead. As anticipated, the analysis of variance indicated that year and location were a source of variation for most of the variables measured. Yearly climatic conditions are not predictable before growers make initial agronomic decisions on cultivar and fertilizer rate. With years and locations considered as random effects, overall conclusions could be made on the relative merits of the different cultivar and N rate treatments beyond the specific year and locations included in this study. Yang (2010) proposed that in agronomic studies it may be more suitable to consider environment effects and their interactions with fixed effects as random because the goal of most crop improvement programs is to ascertain future performance at many untested locations.

### 3.3.1. Plant height

There was no significant interaction between cultivar and N rate for plant height ($P$= 0.3652) (Table 3-4). Increasing nitrogen fertilizer rate resulted in a significant linear increase in plant height, with all cultivars increasing in height with increasing nitrogen fertilizer rates ($P < 0.05$) (Table 3-5). Stride was the tallest cultivar, with an average height of 102 cm (Figure 3-1). The shortest cultivar was CDC Morrison with an average height of 94 cm which was not significantly different than CDC Sea Biscuit. Increases in height of oat by increasing rates of nitrogen fertilizer have been reported previously (Mohr et al. 2007; Peltonen-Sainio et al.1993).

### 3.3.2. Lodging

There was a significant cultivar by nitrogen fertilizer rate interaction observed in crop lodging ($P$<0.0001) (Table 3-4), with increasing nitrogen fertilizer rates resulting in an increase in lodging score of all cultivars (Figure 3-2). Crop lodging was significantly affected by oat cultivars ($P$=0.0003). Stride lodged the most, whereas CDC Morrison lodged least, particularly at the highest N rate (Figure 3-2). The statistical results indicate there was no significant difference between Stride, CDC Norseman and Sea Biscuit (Table 3-6). Stride lodged more than the AC Morgan and CDC Morrison at high nitrogen fertilizer rates which probably explains the cultivar by N rate interaction ($P$<0.0001). There was a weak positive relationship between lodging and grain yield (r =0.32) $P$<0.05. Previous studies have similarly reported increased lodging with increasing rates of nitrogen. May et al. (2004) reported a linear response to lodging in CDC Pacer and AC Assiniboia with increased nitrogen fertilizer rates.

Despite the agronomic characteristics of the Stride on resistance to lodging to be considered as good, the lodging score of Stride increased at the higher rates of nitrogen fertilizer more than the other cultivars. Lodging presented serious harvesting difficulties at Barrhead in 2016. The agronomic treatments, cultivar and fertilizer rates, studied in this experiment have an effect on lodging and in turn lodging can affect seed yield and quality.

**3.3.3. Test weight**

The two-way interaction between oat cultivar and nitrogen fertilizer rates for test weight was not significant ($P$ =0.4425) (Table 3-4). There was a significant cultivar effect on test weight ($P$ = 0.0011), average test weight of Stride and AC Morgan tended to be higher than CDC Sea Biscuit across all nitrogen fertilizer rates.

Test weight was not significantly affected by nitrogen fertilizer rates ($P$ =0.2109), (Table 3-4). Hence, test weight did not differ between high or low rates of nitrogen fertilizer treatment. Several other studies have reported decreases in test weight when levels of applied fertilizer were increased (Knaggs 2002). The reduction in test weight was perhaps due to a possible increase in number of tillers. Seeds on advanced maturing tillers would not be as well filled as on main culms as conditions become warm and dry during grain filling.

**3.3.4. Thousand kernel weight**

Kernel weight was not significantly affected by cultivar and N fertilizer rate treatments (Table 3-4). Although average 1000-kernel weight was not significantly different for nitrogen fertilizer treatments, kernel weights at high levels of nitrogen fertility tended to be lower than the low level of fertility. There was a slight decrease in the kernel weight of all cultivars as nitrogen rate increased (Figure 3-4). Brinkman and Rho (1984) found kernel weight respond negatively to increasing rates of N fertilizer application causing them to decrease. Perhaps, with high levels of nitrogen fertility a higher proportion of tertiary seeds (smaller sized) are formed. Also, the plants tend to produce more tillers and a large number of seeds per panicle both of which might contribute to reduced average kernel weight.

**3.3.5. Percent plump kernel**

A significant cultivar nitrogen interaction was not found for plump kernels (*P*= 0.3032) (Table 3-4). Plump kernel was significantly affected by cultivar (*P* =0.0295), highest percent kernel plumpness was found in AC Morgan (92.6%) which had no difference from CDC Sea Biscuit, (90.9%) and CDC Norseman (88.3%), while Stride and CDC Morrison had the lowest percent plump kernels (85.7%) and (86%) respectively, that was significantly different from AC Morgan (Table 3-6). Correspondingly, AC Morgan had significantly lower thin kernels (7.3%), while CDC Stride and CDC Morrison resulted in higher thin kernels (14.2%) and (13.9) respectively in this study.

A decrease in the percentage of plump seed was observed in all cultivars as nitrogen fertilizer rate increased (Figure 3-5).

Zhou et al. (1998) studied the effect of N and oat cultivar on quality and they determined that cultivar is the key determinant of kernel size across the environments studied. The cultivars 'Echidna', 'Euro', 'Mortlock', and 'Yarran' maintaining consistently higher percentage of plump kernels versus lower percentage of 'Cooba' and 'Bimbil'. Previous studies have reported that increasing N fertilizer rate was a major factor affecting oat yield and quality, and could result in decreased percent plump kernels (May et al. 2004), a trend that was observed in this study. The milling value of oat cultivars is mainly dependent on the size of the kernels. Plump oat kernels are used to make the choice grades of large oat flakes and therefore are most desirable.

### 3.3.6. Grain yield

Oat grain yield was significantly affected by cultivar ($P$=0.0421) and nitrogen fertilizer rate ($P$ < 0.0005). There was no significant interaction between cultivar and N rate interaction found for grain yield ($P$=0.4197), (Table 3-4). This is consistent with previous research conducted in western Canada. Mohr et al. (2007) reported nitrogen fertilizer application significantly increased grain yield in a study conducted in Manitoba. Hamill (2002) reported that the yield of AC Assiniboia and OT288, an experimental breeding line were maintained, while that of two other oat cultivars declined as the applied nitrogen rate increased from 80 to 120 kg $ha^{-1}$. In this study, the highest grain yield (7144 kg $ha^{-1}$) was attained in AC Morgan, whereas CDC Morrison (5739 kg $ha^{-1}$) was the lowest yielding cultivar (Table 3-6).

An absence of an interaction between cultivar and nitrogen has been previously reported (Peltonen-Sainio et al. 1993; Knaggs 2002). As the rate of applied nitrogen fertilizer increased, the yield of cultivars increased at a linear rate ($P$ < 0.0153) (Table 3-5), there was no significant quadratic response to nitrogen fertilizer. (Figure 3-7). Forsberg and Reeves (1995) recognized fertilization management is dependent on the indigenous soil nutrient level in a growing environment.

It is interesting to note that AC Morgan, released in 1999 has not been superseded by new varieties in many yield and quality parameters. This may indicate less intensive breeding research conducted in oat than in other cereals or it may reflect a change in breeding objectives, moving to grain quality for milling rather than yield to increase grower profitability.

### 3.3.7. β-glucan content

Significant differences ($P < 0.0026$) were found between β-glucan content of cultivars (Table 3-7). The highest average β-glucan content was found in CDC Morrison. AC Morgan had significantly lower β-glucan content than other cultivars. CDC Morrison is more suitable for meeting milling 'heart healthy' specification in comparison to AC Morgan. CDC Norseman offers a potential for similar yields to AC Morgan, while maintaining high β-glucan levels in comparison to the most widely grown cultivar in Alberta. Although year was considered a random effect, it was verified that the effect of year on average β-glucan content oat was not significant. There were no differences in average β-glucan content of cultivars regardless of the year of cultivation; differences between oat cultivars were consistent between years with no disparity in cool, rainy years in comparison to dry years. Generally, the relative amounts of β-glucan of the oat cultivars were consistent for different years of cultivation and location which indicates extensive genetic regulation of β-glucan synthesis in oat. This contradicts the finding of Peterson (1991), who found significant differences in oat β-glucan content among nine environments. It is possible that the environmental conditions prevailing at St. Albert and Barrhead were not sufficiently different to result in β-glucan concentration differences. It has been widely reported that the effect of genotype on β-glucan content of oat is significant (Wang et al. 2016; Saastamoinen et al. 2004; Doehlert et al. 2001) and that the β-glucan content of cultivated oat species is quantitatively inherited trait influenced by several genes (Cervantes-Martinez et al. 2001). More recently, Redaelli et al. (2013) investigated the effects of cultivar and environment on β-glucan content for 11 oat cultivars grown in five locations across Europe and found that all factors: location, cultivar, and their interaction, had significant effects on the β-glucan content however in these experiments environmental variance may have been higher.

## 3.4. Conclusions

Cultivar and nitrogen fertilizer rate influence both the yield and quality of oats grown in Alberta. Cultivar had a significant effect on grain yield, plant height, lodging, seed test weight, and kernel plumpness, thins and β-glucan, but not thousand kernel weight (Table 3-4). Nitrogen rate significantly affected grain yield, plant height, lodging and kernel plumpness and thins. With the exception of lodging, cultivar by N rate interaction was not significant for any of the variables investigated, indicating that cultivars responded similarly to nitrogen fertilizer rate. Results of the current study indicate there was a linear increase in grain yield of cultivars when nitrogen rate increased from 5 to 150 kg ha $^{-1}$. Higher nitrogen fertilizer rates resulted in declines in physical grain quality and increased in lodging. Kernel weight, plump kernels and test weight were the physical grain quality parameters that decreased as the rate of nitrogen was increased. The relationships between nitrogen fertilization and milling quality such as test weight and percent plump kernels suggest that while increasing nitrogen increases grain yield it may consequently decrease grain quality.

There was a disadvantage in pushing oat yield at higher nitrogen levels. This subsequently pushed the crop out grade milling grade. Canadian Oat Milling have raw oat specifications based on parameters driven by the end use market. Millers prefer oats with test weights of 54 kg hL$^{-1}$ or more. Oat with test weight less than 53 kg hL$^{-1}$ is rejected. Also, a maximum of 7% thin seed is acceptable with a $1.5/MT deduction for each 1.0% over 7.0%, oat with thin kernels more than 10% is rejected.  A minimum of 70% plump seed is acceptable on bid basis, with a price dockage on plump kernels below 90%. However, plump kernels less than 70% are rejected.

In our study none of the oat cultivars met this milling specification, with the Stride oat recording highest test weight of 49 kg hL$^{-1}$. For plump kernels all cultivars in this study met the minimum acceptable requirements of 70% set by Canadian Oat Milling, however percent plump kernels CDC Norseman, CDC Morrison and Stride were below 90% and as such would be discount in the current milling market. Increasing nitrogen fertilizer rates from 5 to 150 kg $ha^{-1}$ resulted in a decrease in plump kernels from 90 to 88%. At the 50 kg $ha^{-1}$ threshold the proportion of thin kernels being produced no longer met the milling specification (10.82%). This oat would not make milling grade and as such would be rejected based on the requirements set by the Canadian Millers. Cultivars evaluated in this study had significantly different proportions of thin kernels ranging from 7 to 14%.

CDC Norseman offers a potential for similar yields and oat grain quality, while maintaining high β-glucan levels in comparison to AC Morgan. In areas of central Alberta where lodging occurs frequently, due to the relatively high amounts of organic matter soils, selection of cultivars with relatively low lodging potential such as AC Morgan may be appropriate. Stride's high susceptibility to lodging suggests that it may not be suitable for areas of central Alberta where oat is prone to lodging due to high moisture. Results from this study clearly show that in order to increase the possibility of producers growing a profitable oat crop in Alberta, the right cultivar selection in addition to optimum nitrogen fertilizer rate of 150 kg $ha^{-1}$ would be ideal to increase grain yield while maintaining oat quality.

Evaluation of cultivars only under conditions of optimum fertility levels can be misinforming, particularly for yield performance. Mostly, fertility levels of field plots on which most yield experiments are conducted, are high in relation to those of many commercial fields. It is essential to find a balance between maximum yield and quality in nitrogen management for oat. Although nitrogen fertilization may impact specific quality parameters, whether fertilizer management influences the suitability of oats for a given market, or the value of oats, will depend on whether oats meet the quality specifications set by a given grain miller.

An intermediate market between milling and feed markets where additional profitability could be attained for Alberta grown oat is the Pony oat market. Pony oats service a very selective customer base, in the high end race and competitive horse markets. Minimal foreign material, no wild oat seeds, bright plump kernels with preferred test weight of 53 kg $hL^{-1}$.

Manitoba and Saskatchewan are the source of oats for Quaker Oats and General Mills. This is due to market proximity and good quality. Price factors that drive the oat markets include transportation, quality of oat and Canadian, US and Scandinavian supply and demand.

Oat has a potential to be a high yielding and valuable crop, however most Alberta growers are not optimizing oat agronomic practices. Although this research focused on cultivar and nitrogen levels, seeding rates and early time of seeding are also compromised for oat crops and grass weed control is limited by available herbicides. This is reflected in the average oat yield in central Alberta in 2016 of 3159 kg $ha^{-1}$ which compared to average yields in these small plots over three years for AC Morgan of 7146 kg $ha^{-1}$. Unless price differentiation is adopted for β-glucan levels, it is likely that Alberta growers will continue to choose high yielding AC Morgan as their variety of choice to maximize profitability.

**Table 3-1.** Yield and agronomic characteristics of the five oat cultivars used in the cultivar x N study comparable to CDC Dancer.

| Cultivar | Average yield (kg $ha^{-1}$) | Plump (%) | Height (cm) | TKW (g) | Resistance to lodging | Maturity |
|---|---|---|---|---|---|---|
| AC Morgan | 3976+ | 82 | 92 | 40 | very good | medium |
| CDC Morrison[γ] | 3510 | 83 | 87 | 42 | very good | late |
| CDC Norseman | 3617 | 81 | 84 | 38 | good | medium |
| CDC Sea biscuit | 3976+ | 89 | 101 | 41 | good | early |
| Stride | 3725+ | 80 | 104 | 35 | good | medium |
| CDC Dancer | 3582 | 86 | 90 | 37 | good | early |

Alberta seed guide (2016); [γ] Saskatchewan seed guide (2016).

**Table 3-2.** Summary of climatic conditions (May to August) at each location in 2014, 2015 and 2016

| | 2014 | 2015 | 2016 | LTA |
|---|---|---|---|---|
| Location | Total precipitation (mm), % of 30 Year LTA | | | |
| Barrhead | 214 (76%) | 135 (48%) | 413 (146%) | 281 |
| St. Albert | 265 (98%) | 131 (48%) | 297 (110%) | 268 |
| | Average temperature (C) | | | |
| Barrhead | 14.6 | 15.2 | 15.1 | 13.8 |
| St. Albert | 14.5 | 15.2 | 15.2 | 14.6 |

Precipitation and temperature data collected from the closest available Alberta weather station data recorders.
LTA: Long term average.
Values in parentheses are % of LTA.

**Table 3-3.** Soil classification and characteristic for each location.

| | | | | Soil nutrients (ppm) | | | |
|---|---|---|---|---|---|---|---|
| Location | Soil characterization | pH | OM (%) | $NO_3$-N | $P_20_5$ | $K_2O$ | S |
| Barrhead | Dark gray Chernozem | | | | | | |
| 2014 | | 6 | 6.3 | 15 | 26 | 181 | 17 |
| 2015 | | 5.7 | 6.1 | 15 | 28 | 187 | 31 |
| 2016 | | 5.7 | 6.0 | 15 | 26 | 182 | 30 |
| St. Albert | Black Chernozem | | | | | | |
| 2014 | | 6.6 | 11 | 8 | 41 | 345 | 33 |
| 2015 | | 6.9 | 10.3 | 11 | 24 | 311 | 16 |
| 2016 | | 8.1 | 11.4 | 14 | 50 | 304 | 14 |

Soil orders in the Canadian system of soil classification.

Abbreviations: OM: organic matter, $NO_3$-N: Nitrate, $P2O_5$: Phosphate, $K_2O$: Potassium.

Soil characteristics taken at 0-15 cm depth.

Table 3-4. *P* values from the analysis of variance for the effects (fixed) of cultivar and N rate, and their interaction on oat variables. Location, years and replicates were considered random. Significant (*P*<0.05) effects are in bold

| Grain yield | | | |
|---|---|---|---|
| Effects | F value | df | *P* value |
| Cultivar | 5.26 | 4 | **0.0421** |
| N rate | 7.39 | 3 | **0.0005** |
| Cultivar x N rate | 0.61 | 12 | 0.4197 |
| **Plant height** | | | |
| | F value | df | *P* value |
| Cultivar | 14.16 | 4 | **0.0010** |
| N rate | 8.47 | 3 | **0.0031** |
| Cultivar x N rate | 1.09 | 12 | 0.3652 |
| **Lodging** | | | |
| | F value | df | *P* value |
| Cultivar | 16.84 | 4 | **0.0003** |
| N rate | 76.2 | 3 | **<0.0001** |
| Cultivar x N rate | 18.6 | 12 | **<0.0001** |
| **Test weight** | | | |
| | F value | df | *P* value |
| Cultivar | 6.96 | 4 | **0.0011** |
| N rate | 1.72 | 3 | 0.2109 |
| Cultivar x N rate | 0.99 | 12 | 0.4425 |
| **TKW** | | | |
| | F value | df | *P* value |
| Cultivar | 1.58 | 4 | 0.3339 |
| N rate | 0.80 | 3 | 0.4621 |
| Cultivar x N rate | 1.40 | 12 | 0.2640 |
| **Plumps** | | | |
| | F value | df | *P* value |
| Cultivar | 4.56 | 4 | **0.0295** |
| N rate | 7.32 | 3 | **0.0040** |
| Cultivar x N rate | 1.29 | 12 | 0.3032 |
| **Thins** | | | |
| | F value | df | *P* value |
| Cultivar | 4.57 | 4 | **0.0300** |
| N rate | 4.67 | 3 | **0.0138** |
| Cultivar x N rate | 1.2 | 12 | 0.3643 |

**Table 3-5.** N response on yield, height, lodging and quality parameters.

| Effect | Yield (kg $ha^{-1}$) | Height (cm) | Lodging (1-5) | Test weight (kg $hL^{-1}$) | TKW (g) | Plumps (%) | Thins (%) |
|---|---|---|---|---|---|---|---|
| N linear | **0.0153** | **0.0346** | **0.0286** | 0.302 | 0.3022 | 0.0624 | 0.0626 |
| N quadratic | 0.1498 | 0.2038 | 0.7916 | 0.408 | 0.4086 | 0.3058 | 0.3063 |

Table 3-6. The effect of cultivar on yield, height, lodging and quality parameters for oat (mean of 6 site-years).

| Effect | Yield (kg $ha^{-1}$) | Height (cm) | Lodging (1-5) | Test weight (kg $hL^{-1}$) | TKW (g) | Plumps (%) | Thins (%) |
|---|---|---|---|---|---|---|---|
| Cultivar | | | | | | | |
| AC Morgan[z] | 7146.7b | 99.2cd | 1.8ab | 48.3b | 36.9a | 92.6b | 7.3a |
| CDC Morrison | 5739.9a | 94.4a | 1.4a | 47.3ab | 31.8a | 86.0a | 13.9b |
| CDC Sea Biscuit | 6282.8ab | 96.1ab | 2.4bc | 45.7a | 35.0a | 90.9ab | 9.0ab |
| CDC Norseman | 6695.6ab | 98.7bc | 2.5bc | 46.7ab | 35.3a | 88.3ab | 11.6ab |
| Stride | 6312.4ab | 102.1d | 3.0c | 49.1b | 30.9a | 85.7a | 14.2b |
| SE | 1145 | 13.78 | 0.37 | 2.69 | 4.66 | 2.5 | 2.46 |

[z] Means within a column followed by the same letters are not significantly different at ($P< 0.05$), using Tukey's HSD pairwise comparisons with a confidence level of 0.95.

**Table 3-7.** Effect of oat cultivar on β-glucan content (%). Location and replicates within location were considered random.

| Cultivar | LSMeans (%) | SEM | Significance $P < 0.01$ |
|---|---|---|---|
| AC Morgan | 3.77 | 0.09 | a |
| CDC Morrison | 5.85 | 0.09 | d |
| CDC Sea Biscuit | 4.38 | 0.09 | b |
| CDC Norseman | 5.00 | 0.09 | c |
| Stride | 4.38 | 0.11 | b |
| | | | |
| F-test | F value | P value | |
| Cultivar | 195.8 | 0.0026 ** | |
| Year | 0.752 | 0.5450 | |
| Cultivar x Year | 4.961 | 0.0386 * | |

*, **, indicate $P < 0.05$ and 0.01 respectively.

LSMeans: Least square means.

SEM: Standard error of means.

Significance: a b, c, d cultivars marked with different letters differ significantly from each other.

Table 3-8. Pesticides applied to plots at Barrhead and St. Albert from 2014-2016

| Site | Chemical | Application rate | Target Pest |
|---|---|---|---|
| | **Herbicides:** | | |
| | Spectrum A | 0.1 L $ha^{-1}$ | |
| Barrhead | Spectrum B | 1.48 L $ha^{-1}$ | lamb' quarters |
| St. Albert | Frontline XL | 1.24 L $ha^{-1}$ | wild buckwheat |
| | **Fungicides:** | | |
| Barrhead | Caramba | 1 L $ha^{-1}$ | crown rust |
| St. Albert | Headline | 0.3 L $ha^{-1}$ | crown rust |
| | **Dessicants:** | | |
| Barrhead | Reglone | 1.7 L $ha^{-1}$ | n/a |
| St. Albert | Reglone | 1.7 L $ha^{-1}$ | n/a |

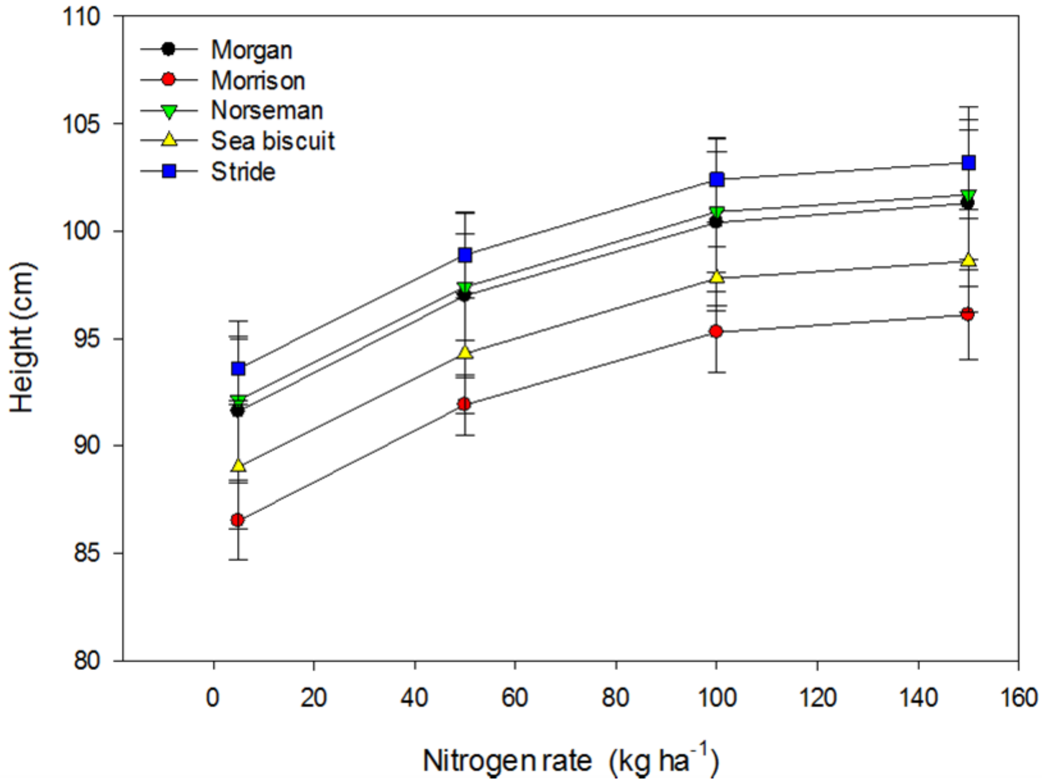



**Figure 3-1.** Height least squares means (LSmean) as affected by increasing N rates averaged over cultivars (error bars indicate SE).

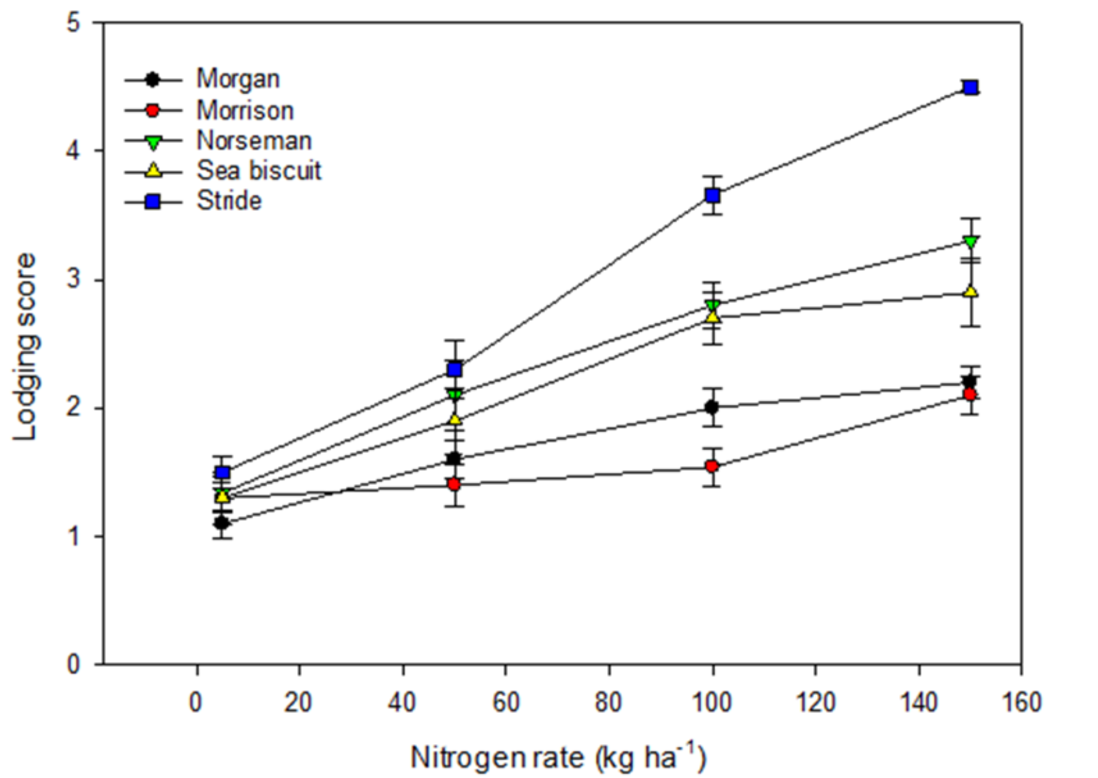



**Figure 3-2.** Lodging least squares means (LSmean) as affected by increasing N rates averaged over cultivars (error bars indicate SE)

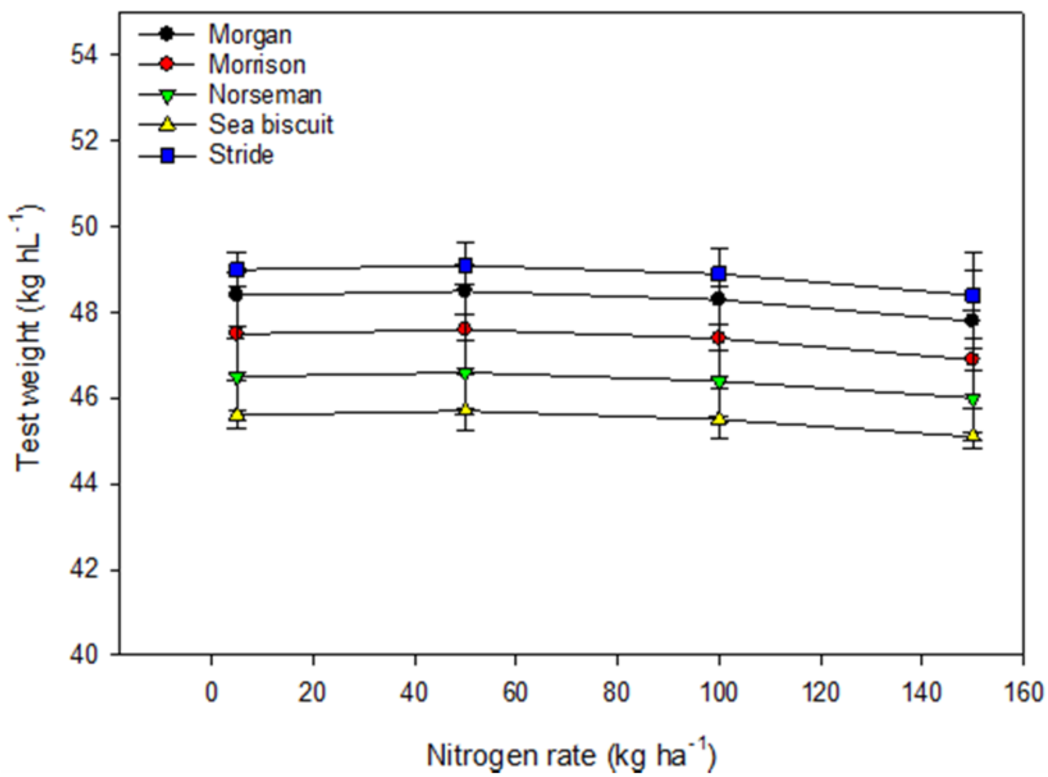



**Figure 3-3.** Test weight least squares means (LSmean) as affected by increasing N rates averaged over cultivars (error bars indicate SE)

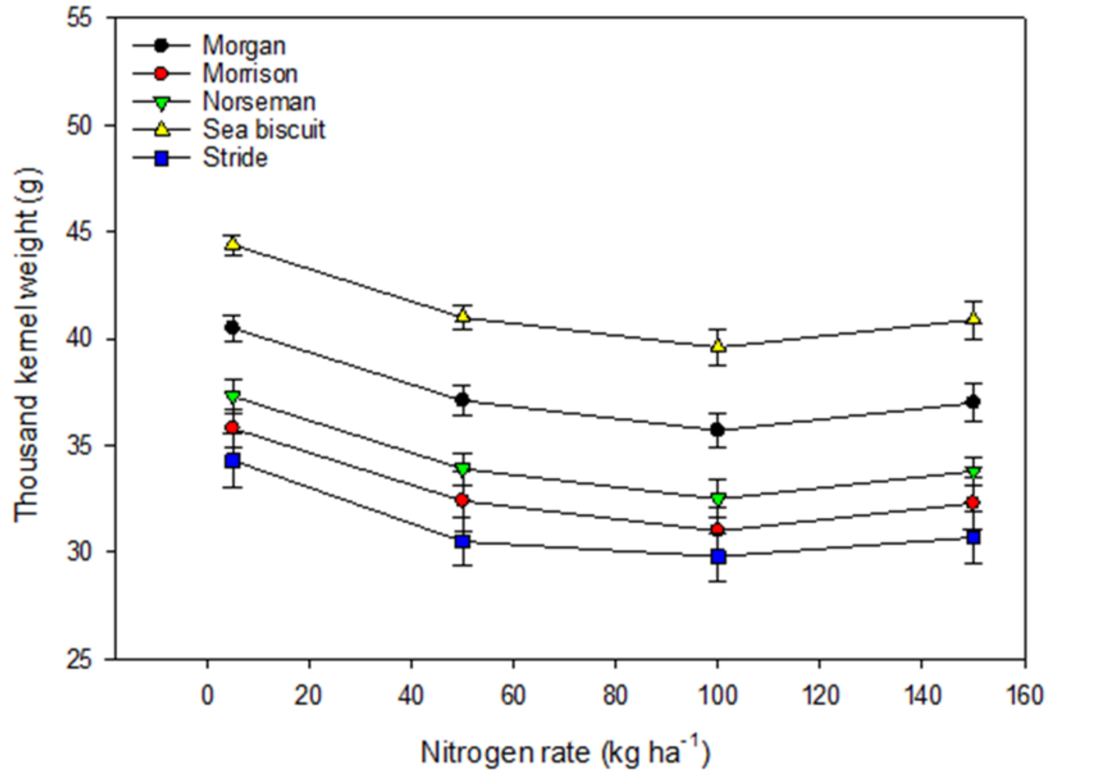



**Figure 3-4.** Thousand kernel weight least squares means (LSmean) as affected by increasing N rates averaged over cultivars (error bars indicate SE)

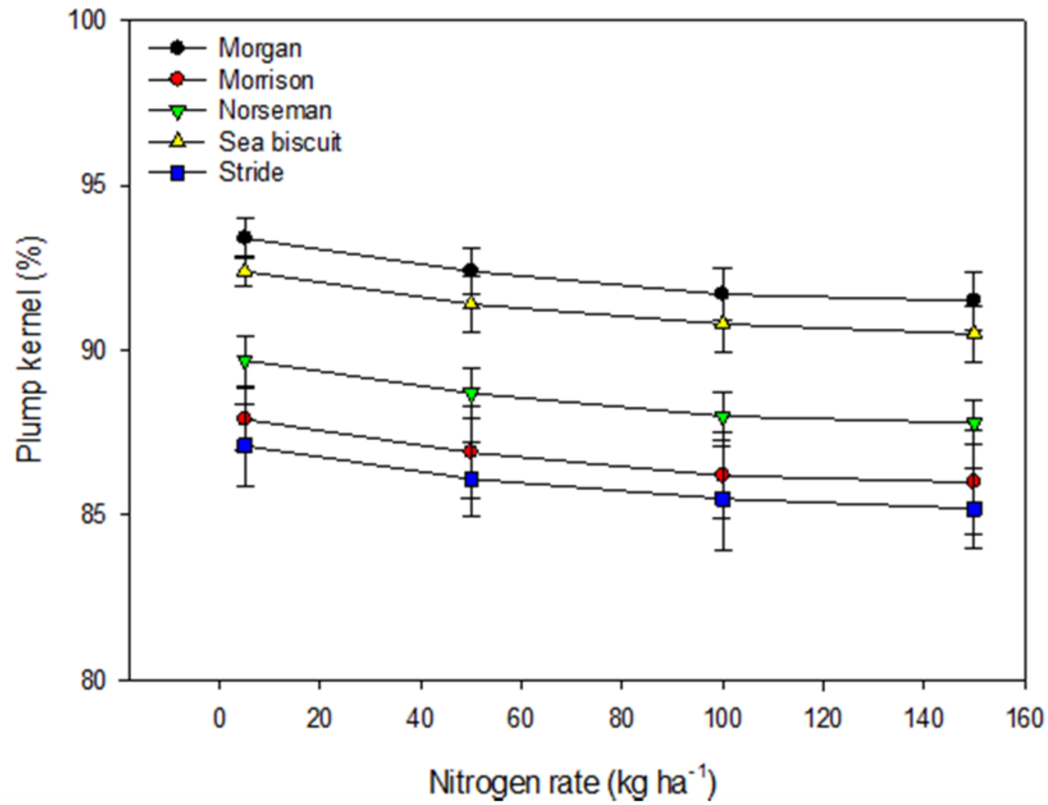



**Figure 3-5.** Plump kernel least squares means (LSmean) affected by increasing N rates averaged over cultivars (error bars indicate SE)

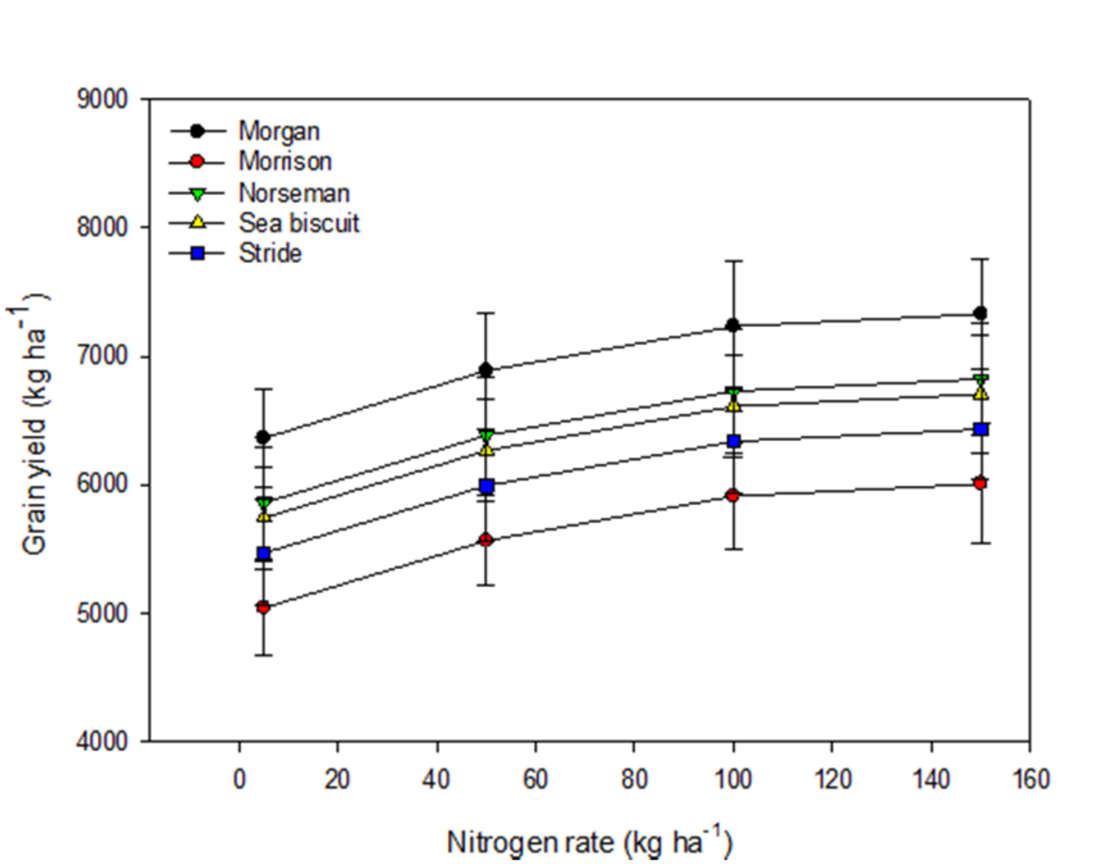



**Figure 3-6.** Oat grain yield least squares means (LSmean) affected by increasing N rates averaged over cultivars (error bars indicate SE)

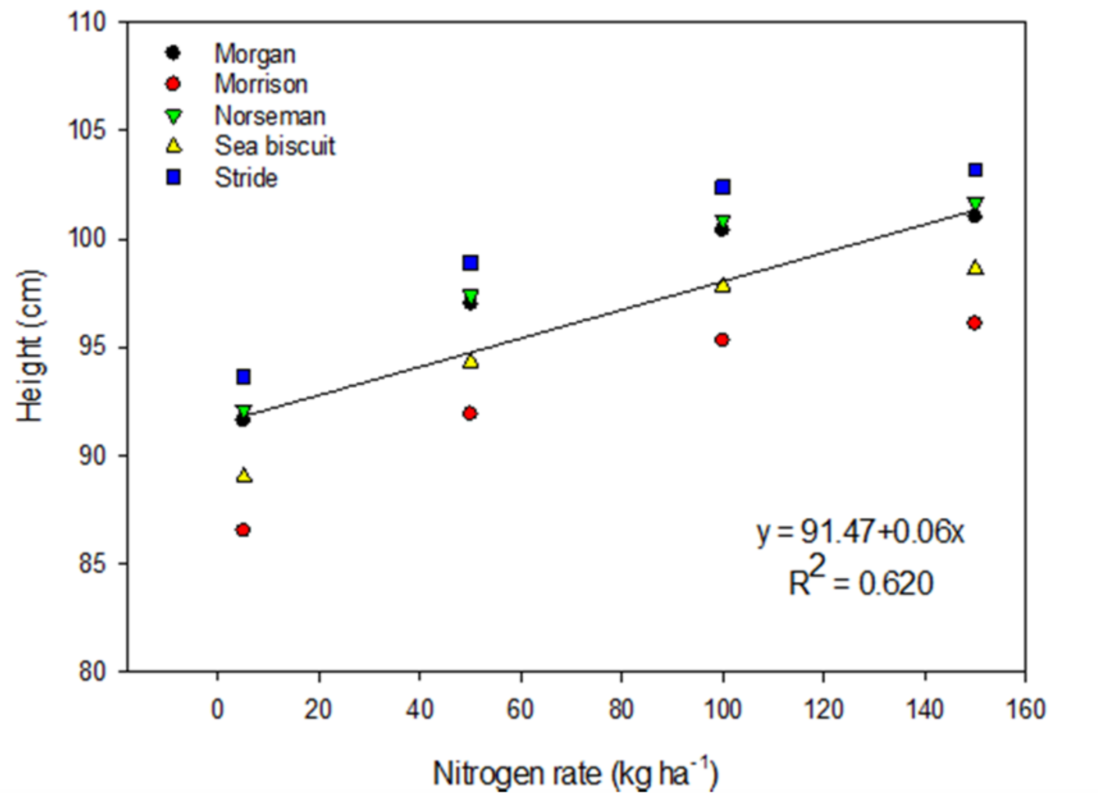



**Figure 3-7** Effect of increasing N rates on height of oat. The regression equation and line reflect data averaged over cultivars

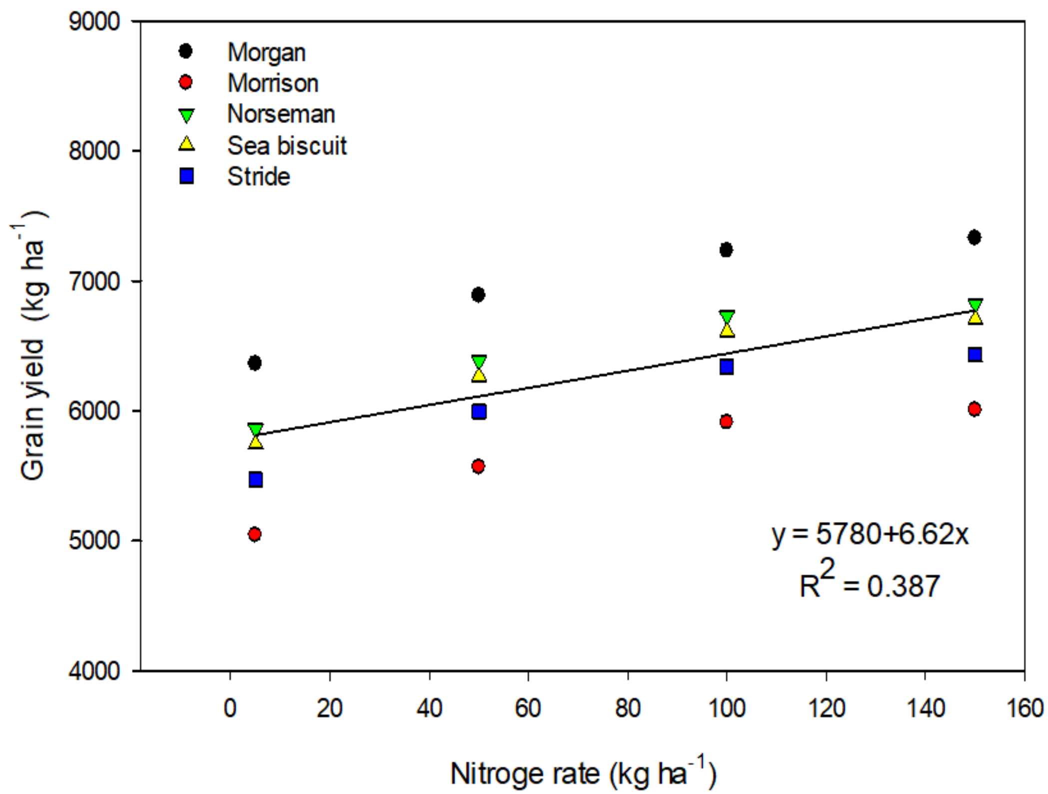



**Figure 3-8.** Effect of increasing N rates on gain yield of oat. The regression equation and line reflect data averaged over cultivars

# Chapter Four: Effect of plant growth regulator application and nitrogen fertilization on oat yield and lodging

## 4.1. Introduction

Oat (*Avena sativa* L.) is a competitive cereal crop well-suited to the Parkland region of central and northern Alberta. Oat competes with the higher value crops canola, wheat and malt barley and only occupies only 1.3 million hectares. Grower profitability depends on achieving high yield and grain quality which are difficult to achieve simultaneously (Chapter 3). For the higher value milling market, quality standards vary. Some markets may require higher β-glucan content, which is cultivar and environmental dependent (Saastamoinen et al. 2008) (Chapter 3). Other markets require a minimum test weight of 245 g/0.5 L, a minimum 1000 grain weight of 27 g, 26% maximum hull content, minimum 90% plump kernels, moisture content of <15%, double oat (poorly developed groats) present not exceeding 0.8%, a 1% allowable foreign material and maximum foreign grain of 3% maximum (Ganssmann and Vorwerck, 1995). By increasing nitrogen fertilizer, yield increases can be achieved, but at the expense of seed quality and an increase in lodging.

Oats yield are detrimentally affected by lodging, a condition where plants bend excessively or break. (Berry et al. 1998). Lodging is influenced by cultivar, available nitrogen fertilizer (May et al. 2004) and available moisture, but is also influenced by wind and rain events (Kelbert et al. 2004). Lodging at the beginning of the grain filling period has been reported to reduce grain yield by between 50% and 80% (Stapper and Fischer, 1990; Easson et al. 1993) but later lodging is less detrimental to yield. Lodging can negatively affect seed quality through the interruption of the grain filling process (Berry et al. 2004). This is as a result of reduced supply of assimilates and nutrients to the grain head. For growers, lodging increases harvesting difficulties.

Plant growth regulators (PGRs) have proven effective in reducing plant height, and lodging, and thereby maintaining grain yield, and are considered a vital part of intensive cereal production in many countries (Knapp and Harms, 1988; Van Sanford et al. 1989). The PGR trinexapac-ethyl (ethyl(3-oxido-4-cyclopropionyl-5-oxo) oxo-3-cyclohexenecarboxylate) is being tested for reduction of lodging in cereals in Canada. Trinexapac-ethyl inhibits the enzyme 3β-hydroxylase, a key enzyme in the gibberellin biosynthesis pathway, which reduces the level of active gibberellic acid $GA_1$ (Rademacher, 2000). Foliar application significantly decreases stem elongation of durum plants, reducing lodging and limiting yield losses (Nolte, 2007). Marolli et al. (2017) reported a trinexapac-ethyl rate of 120 g a.i $ha^{-1}$ reduced lodging with low, high and very high use of N-fertilizer, without reducing the yield of oat grain, in a favorable, intermediate or unfavorable year for cultivation. Regardless of the condition of the year, the growth regulator dose of 120 g a.i $ha^{-1}$ did not reduce grain yield and allowed effective reduction of lodging in their study. Trinexapac-ethyl rates of 0, 50 and 100 g a.i. $ha^{-1}$ did not alter grain yield in intermediate and unfavorable years. In a favorable year, regardless of the growth regulator rate, grain yield was not affected. Lodging in this condition was drastically reduced, indicating that 100 g a.i. $ha^{-1}$ also improves standability. The years with highest grain yield, especially at high doses of nitrogen fertilizer, high lodging percentage was obtained in the absence of the growth regulator. Matysiak (2006) evaluated two trinexapac-ethyl rates (75 and 125 g a.i $ha^{-1}$) and concluded the effects were dose dependent, with the higher dose more effective in shortening plants and maintaining grain yield and protein content. Penckowski et al. (2009) reported that a trinexapac-ethyl rate of 100 g a.i. $ha^{-1}$ applied between GS 31 and 33 resulted in an increase in wheat grain yield and spikelets per head. PGRs may well allow growers to increase nitrogen to increase yield while reducing lodging, increasing harvestability and reducing grain spoilage. However, any benefits associated with high nitrogen and PGRs will only be apparent under good growing conditions, when moisture is not limiting. Because PGRs are applied near stem elongation, seasonal available moisture may be more accurately predicted that at seeding.

Stride oat is a conventional, tall, white-hulled, disease resistant cultivar developed by Agriculture and Agri-Food Canada, Cereal Research Centre (AAFC-CRC), Winnipeg, MB (Mitchell Fetch et al. 2013). Stride oat has lower yield potential than AC Morgan, the most widely grown variety in central Alberta, but the β-glucan content is significantly higher than AC Morgan, making it more suitable for some milling markets.

The objective of this study was to determine the effect of trinexapac-ethyl rate and nitrogen fertilization rates on grain yield, lodging and related agronomic responses of Stride oat at three sites, examined over a 3-year period. We hypothesized that trinexapac-ethyl would be most useful in growing conditions where lodging risk and yield potential was high.

## 4.2. Materials and methods

Field experiments were conducted at Barrhead (lat. 54° 7' N, long. 114° 24' W), St. Albert, AB (lat. 53° 37' N, long. 113° 37' W) and Indian Head, SK (lat.50° 33' N, long. 103° 39' W) (Figure 4-1) from of 2014 to2016 by direct seeding Stride oat into canola stubble in early- to mid-May. The experiment was designed as a randomized complete block with four replicates. The factorial arrangement of treatments included four rates of trinexapac-ethyl (0, 70, 100 and 130 g a.i $ha^{-1}$) and four nitrogen fertilizer rates (5, 50, 100 and 150 N kg $ha^{-1}$).

Soil samples were collected in the spring near the time of seeding. The nitrogen fertilizer was applied as urea (46-0-0) at seeding. Urea and potassium sulphate fertilizer were side-banded while monoammonium phosphate was placed in the seed row. A total of 44-50-16 kg P2O5-K2O-S $ha^{-1}$, 24-0-29 kg P2O5-K2O-S $ha^{-1}$ 35-35-12 kg P2O5-K2O-S $ha^{-1}$ at Barrhead St. Albert and Indian Head respectively was supplied to all treatments while N rates varied as per protocol. Oat was seeded into six rows at a seeding rate of 450 viable seeds $m^{-2}$ into experimental plots that measured 8.5m x 1.2 m using a Fabro® double disc opener with a 25 cm row spacing at Barrhead and a Fabro® air seeder equipped with double shoot Atom jet hoe openers with 20 cm row spacing at St. Albert and a Conservapak air seeder with a 30 cm row spacing at Indian Head. Trinexapac-ethyl was applied in 100 L $ha^{-1}$ of water volume at 30 psi at growth stage 31, the early stem elongation stage between the first and second noticeable node 1 cm above the tillering node (Zadoks et al. 1974) using a high clearance research sprayer at Barrhead, a Bellspray research sprayer at St. Albert and a self-propelled high clearance sprayer at Indian Head. All sites used a Teejet XR 110105 low drift nozzle. Plant height was measured from the ground surface to the top of the culm (excluding the awn) at maturity by averaging five measurements per plot. Lodging at physiological maturity was evaluated using a lodging index (1 = upright or 90° to 5 = flat or 0°, relative to the ground) (Wiersma et al. 1986). At maturity, each plot was harvested using a small plot Wintersteiger combine at Barrhead and St. Albert while a Kincaid XP combine harvester was used at Indian Head. Grain samples were dried to constant moisture (13.5%), cleaned and the grain weight recorded. Seed test weight was measured using methodology specified by the Canadian grain commission (1998). Percent plump grain was determined by the weight of a 50g sample that did not pass through a 5.5/64 by ¾ inch slotted sieve, with double oat removed prior to sieving. The grain remaining on top of the 5.5/64 by ¾ inch slotted sieve was weighed and considered as plump seed. Growing season precipitation data was collected from nearby weather stations (Table 4-2).

Data was fit to a linear mixed model with the LME4 procedure of R (Bates et.al, 2014) and subjected to ANOVA in the nlme package, and LSmeans analysis in the LSmeans package of R (v. 0.98.1091). Data from all site years were evaluated for homogeneity of error variances using a Bartlett's test. Analysis was conducted separately for each site to allow comparison of the effects of fertilizer and trinexapac-ethyl treatments over a wide range of environmental conditions due to PGR and site interactions. The year of cultivation, PGR and nitrogen rate were considered as fixed effects. Tukey's least significant difference test was used to make mean comparisons. The effects of N fertilizer and TE rate and interactions with years were assessed with orthogonal polynomial contrasts. A regression equation, describing responses to N fertilizer and TE rates was calculated for the variables of interest when corresponding contrasts were significant ($P < 0.05$). A linear mixed model fit by REML t-tests using Satterthwaite approximations to degrees of freedom was used to compare significant linear and quadratic responses.

## 4.3. Results and Discussion

Soil moisture varied between sites and year from 47 to 157% of normal precipitation. In 2015, Barrhead and St. Albert received 48% of the long-term average precipitation between May and August, creating peculiarly dry growing conditions (Table 4-2), resulting in delayed early-season growth and exceptionally low grain yield. In 2016, precipitation for St. Albert and Barrhead was higher than normal. Due to significant variations in experimental sites (Table 4-3, 4-4), analysis was conducted separately for each site to allow comparison of the effects of the various years of cultivation, plant growth regulator and nitrogen fertilizer treatments over different environmental conditions.

**4.3.1. Grain yield**

Year of cultivation had a significant effect on grain yield at Barrhead and St. Albert (Table 4-5), (Table 4-6). Average grain yields in 2014 at Barrhead and St. Albert were 6403 kg $ha^{-1}$ and 6136 kg $ha^{-1}$, respectively. Whereas, grain yield in the dry year of 2015 was 3116 kg $ha^{-1}$ and 4419 kg $ha^{-1}$ at Barrhead and St. Albert, respectively, representing a 51% and 25% yield reduction.

Low grain yield in 2015 was as a result of an extremely dry spring with low precipitation resulting in moisture stress in the oat crop.

On the contrary, year of cultivation had no significant effect on grain yield at Indian Head ($P$ = 0.5638), (Table 4-7). Grain yields at Indian Head did not differ between a wet and dry year, a pattern that was not observed at other experimental sites (Table 4-5, 4-6). There was an interaction between PGR, nitrogen rate and year of cultivation for grain yield at Indian Head ($P < 0.001$) (Table 4-3). The soil N at this location was higher than the other sites and soil moisture ranged from 76 to 158% of normal (Table 4-2). When growing season precipitation was unfavorable in 2015, (76% of normal) creating dry growing conditions, trinexapac-ethyl had a quadratic response on grain yield, with lowest grain yield recorded at highest N rate (Figure 4-2, B). Kaspary et al. (2015) reported a similar response of yield components and yield to trinexapac-ethyl. However, when precipitation was favorable, grain yield was higher at highest N and PGR rates, probably related to a decrease on lodging.

There were significant interactions between nitrogen rate and year as well as significant interactions between plant growth regulator and year of cultivation observed for grain yield at Barrhead and St. Albert (Table 4-3), possibly because the difference in year of cultivation was so high that influenced the PGR response, which was expected for the interaction with N rate. This interaction occurred as a linear response for PGR in 2016 at both locations, no significant response to PGR in normal (2014) and dry years (2015).

A quadratic N response yield curve in 2014 and 2016, was observed at Barrhead in years when precipitation was normal and wet. Whereas in 2015 the trend was a linear responsive demonstrating the dependence of nitrogen utilization on the availability of adequate moisture (Cooper et al. 1987). The response at St. Albert was a quadratic in 2014, with highest grain yield, while in 2016 the response was linear. Even with high precipitation in 2016, the yield was lower than 2014, and it probably happened because in 2016 the soil had the highest pH (above 8) (Table 4.1), possibly reducing the availabity of trace elements.

In our study, oat yields significantly increased with increasing nitrogen fertilizer rates, peaking at approximately 128 kg $ha^{-1}$ for Barrhead, 150 kg $ha^{-1}$ for St. Albert and 135 kg $ha^{-1}$ for Indian Head. This is consistent with research conducted in western Canada. Mohr et al. (2007) reported nitrogen fertilizer application significantly increased grain yield, moderate nitrogen rates significantly increased yield, with optimum yield attained with plant-available nitrogen supply of approximately is 100 kg $ha^{-1}$.

There was no significant interaction between PGR and nitrogen observed for grain yield at Barrhead ($P$ = 0.1853), and St. Albert ($P$ = 0.6858), indicating that yield response to nitrogen was similar with or without PGR (Table 4-3). PGR application had no significant effect on oat grain yield at Barrhead and Indianhead (Table 4-3). Rajala and Peltonen-Sainio (2002) did not find a significant trinexapac-ethyl treatment effect on the grain yield of oat. Marolli et al. (2017)

conducted a study to determine the effect of trinexapac-ethyl on oat yield. He reported grain yield did not differ between trinexapac-ethyl treatments.

**4.3.2. Plant height**

A three-way interaction between PGR, nitrogen rate and year of cultivation was found for plant height at St. Albert ($P= 0.0094$), (Figure 4-3). Average plant height was shorter in the year with low precipitation (2015), with small variations in increasing N rate (Fig 4-3). In the years with favorable precipitation (2014 and 2016), it was evident the plants were taller, with height having a quadratic response to N rate and trinexapac-ethyl. However, in the dry year (2015), there was a significant linear height response to trinexapac-ethyl.

There were significant interactions between plant growth regulator and year of cultivation as well as significant interactions between nitrogen rate and year of cultivation at Barrhead, St. Albert and Indian Head (Table 4-3) with a height response to PGR treatments in a year with adequate moisture. In a wet year like 2016, when the amount of applied N fertilizer was increased there was a quadratic increase in plant height. in comparison to a dry year such as 2015 when there was no height response at Barrhead (Tables 4-9). In 2016, trinexapac-ethyl rate of 130 g a.i $ha^{-1}$ significantly reduced plant height at Barrhead, St. Albert and Indian Head by approximately 10%, 8% and 7% respectively when compared with the control. Trinexapac ethyl application resulted in a significant linear decrease in plant height at all sites (Table 4-9). Previous studies have similarly demonstrated decreases in plant height with PGR applications. Wiersma et al. (2011) found that trinexapac-ethyl effectively decreased plant height of wheat and that the plant shortening effects of trinexapac-ethyl depended rate. Trinexapac-ethyl rate of 125 g a.i $ha^{-1}$ was reported to cause an approximately 10% reduction in wheat internode length (Zagonel et al. 2002). Penckowski et al. (2009) reported that applications of trinexapac-ethyl at

100 g a.i ha $^{-1}$ between GS 31 and 33 resulted in about 8% reduction in plant height of high yielding wheat. Hawerroth et al. (2015) reported that the application of trinexapac-ethyl growth regulator significantly reduced plant height of oat in different environments. According to Zagonel et al. (2002), growth regulators are effective in reducing the height of wheat plants, regardless of the cultivar.

Our study found a significant trend of increasing plant height in response to increasing rates nitrogen application.

Increases in height of oat by increasing rates of nitrogen fertilizer have been reported previously (Mohr et al. 2007)

**4.3.3. Lodging**

A three-way interaction between PGR, nitrogen rate and year of cultivation was found for lodging at Indian Head (Table 4-3), (Figure 4-6). Differences in lodging were observed between PGR rates and years of cultivation at Indian Head; lodging scores were higher in a wet year (2014) in comparison to a relatively dry year 2015. Lodging response to N rate application was significant in the years 2014 and 2016. No significant lodging response to N was observed in 2015.

PGR effects at St. Albert were dependent on the growing year as indicated by the significant PGR by Year interactions (Table 4-3), with a linear response in 2014 and 2016 (Table. 4-10). Lodging was not usually observed in the 2015 growing season at Barrhead and St. Albert, a year in which moisture was limiting at these experimental sites. Some studies have reported that trinexapac-ethyl significantly decreases stem elongation of cereal plants, subsequently reducing lodging and limiting yield losses (Nolte, 2007; Penckowski et al. 2009). Penckowski et al. (2009)

found that trinexapac-ethyl rate of 100 g a.i. $ha^{-1}$ was effective in reducing lodging in wheat when applied between GS 31-33.

At Barrhead, a significant PGR by Year interaction was observed for lodging ($P$ = 0.0232). Lodging had a significant quadratic response to plant growth regulator in 2016. In this year, the best dose of the trinexapac-ethyl was 67 g a.i. $ha^{-1}$.

Nitrogen application significantly affected lodging, lodging generally increased with increasing nitrogen rates, with high lodging scores observed at higher nitrogen rates. Significant N and Year interaction was observed at all sites. Quadratic response to N observed at St. Albert and Barrhead in 2014 and 2016 (Table 4-10), with a linear response to N in 2016 at Barrhead. No significant N response observed in 2015 at all sites. Previous studies have similarly reported increased lodging with increasing rates of nitrogen. May et al. (2004) reported a linear response to lodging in oat as nitrogen fertilizer rates increased.

**4.3.4. Grain quality**

A significant three-way interaction for PGR x N x Year was found for test weight at Indian Head. (Table 4-4) (Figure 4-7). Test weight was not significantly affected by PGR application at Barrhead ($P$ =0.7002), and St. Albert ($P$ =0.8214) respectively.

(Table 4-4). Test weight did not differ between high or low rates of trinexapac-ethyl treatment when compared to the control at these sites. Previous work done by Wiersma et al. (2011) found that trinexapac-ethyl treatment generally did not affect test weight.

A significant two-way interaction was found for kernel weight between nitrogen and year of cultivation at Indian Head ($P$ = 0.0003), as well as significant two-way interaction for kernel weight between nitrogen and PGR ($P$ = 0.0073) (Table 4-4)

At St. Albert a significant two-way interaction was found for kernel weight between PGR and year ($P$ = 0.0016) (Table 4-9). In a previous study, Wiersma et al. (2011) reported that applications of trinexapac-ethyl did not affect kernel weight.

A significant three-way interaction was found for kernel plumpness, an important grading factor for milling oat at Barrhead (Figure 4-10) and Indian Head (Figure 4-12), (Table 4-4). There were significant interactions between plant growth regulator and year of cultivation as well as interactions between nitrogen rate and year of cultivation at St. Albert (Table 4-4)

A significant nitrogen effect was found for plump kernels at each site (Table 4-4). Previous studies have also reported that increasing nitrogen fertilizer rate was a major factor affecting oat quality, resulting in decreased percent plump kernels. (May et al. 2004).

## 4.4. Conclusions

In some sites and years, where available moisture was high, application of trinexapac-ethyl resulted in a decrease in height and lodging but did not directly affect yields. However, trinexapac-ethyl caused a decrease in grain yield in Indian Head in 2015. The results of this study indicate a strong yield response to nitrogen rate and year of cultivation, with higher yield related to higher nitrogen rates in years with good moisture. Increasing nitrogen fertilizer resulted in increased grain yield in all site-years. At the Barrhead and St. Albert sites, grain yield was significantly lower in 2015, indicating lower yields associated with a dry year where growing conditions were not favorable. The application of the trinexapac-ethyl did not have a significant effect on grain yield of Stride oat; the PGR did not affect grain yield.

The trinexapac-ethyl was effective in reducing plant height and lodging of Stride oat. Although, PGR was effective in reducing plant height and lodging, it provided no real yield benefit in this study. However, at Barrhead and St. Albert in 2016 there was a yield response to increasing rates of trinexapac-ethyl. Our results show that the intensity of the lodging reduction by PGR may depend on the environmental conditions in a growing year, especially when the conditions are favorable for greater growth. Increasing rates of trinexapac-ethyl reduced plump kernels. The use of trinexapac-ethyl did not adversely affect physical grain quality parameters such as test weight and thousand kernel weight. This study indicates that trinexapac-ethyl can be used to effectively control lodging of susceptible cultivars under adequate conditions. It is recommended that this PGR is considered for use in environments conducive to lodging.

That being said, in the absence of lodging PGR treatments would only be cost effective if they increase yield to at least cover application expenditures. Predicting lodging pressure at the beginning of the growing season is difficult, if not impossible. Therefore, PGR's may be considered as insurance on inputs invested, especially for high input growers in high rainfall environments targeting high yields. Trinexapac-ethyl rate of 130 gai-$ha^{-1}$ is ideal for achieving best height and lodging reduction. The environmental condition of the year and nitrogen fertilizer application, could improve the suitability of this tool. Further research should involve evaluating PGR use with intensive management systems such as evaluating PGR interaction with seeding rates, variable PGR rates and timing. For PGR's to generate positive economic outcomes for growers in Western Canada they should be competitively priced and perhaps in the future possess dual functioning compounds to save growers time and improve efficiency, convenience, yields and profitability.

**Table 4-1.** Soil test nutrient analysis and properties for three sites including percent composition of sand, silt, clay, and organic matter.

| Year | Site | Soil texture | Sand | Silt | Clay | OM | Soil pH | Nitrate $NO_3$-N | Phosphate $P_2O5$ | Potassium $K_2O$ | Sulfate S |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | --------------%--------------- | | | (%) | | (mg $kg^{-1}$) | | | |
| 2014 | Barrhead | Clay loam | 17.6 | 40.1 | 42.3 | 6.3 | 6 | 15 | 26 | 181 | 17 |
| | St. Albert | Silty clay | 35.8 | 40.2 | 24 | 11 | 6.6 | 15 | 28 | 187 | 31 |
| | Indian Head | Heavy clay | 20 | 20.4 | 59.6 | 4.3 | 7.4 | 15 | 26 | 182 | 30 |
| 2015 | Barrhead | Clay loam | 16.4 | 43.8 | 22 | 6.1 | 5.7 | 8 | 41 | 345 | 33 |
| | St. Albert | Silty clay | 12.6 | 46.3 | 43.8 | 10.3 | 6.9 | 11 | 24 | 311 | 16 |
| | Indian Head | Heavy clay | 20.4 | 20.6 | 59 | 5.7 | 7.6 | 14 | 50 | 304 | 14 |
| 2016 | Barrhead | Clay loam | 18 | 39.6 | 42.4 | 6 | 5.7 | 7 | 19 | 186 | 4.8 |
| | St. Albert | Silty clay | 19.3 | 44.9 | 35.8 | 11.4 | 8.1 | 5 | 12 | 202 | 5.6 |
| | Indian Head | Heavy clay | 21.2 | 20.7 | 58.1 | 4 | 7 | 6 | 11 | 286 | 3.9 |

Abbreviations: OM, organic matter.
Soil characteristics taken at 0-15 cm depth.

**Table 4-2.** Summary of precipitation during growing season at all experimental sites in 2014, 2015 and 2016.

| Year | Site | Accumulated from May-Aug | Long term Average (LTA) | % of 30 Year Long Term Average |
|---|---|---|---|---|
| | | ------------------------- mm | ------------------------ | --%-- |
| 2014 | Barrhead | 214 | 281 | 76 |
| | St. Albert | 265 | 268 | 98 |
| | Indian Head | 385 | 244 | 157 |
| 2015 | Barrhead | 135 | 281 | 48 |
| | St. Albert | 131 | 268 | 48 |
| | Indian Head | 207 | 244 | 84 |
| 2016 | Barrhead | 413 | 281 | 146 |
| | St. Albert | 297 | 268 | 110 |
| | Indian Head | 255 | 244 | 104 |

Barrhead weather station: Barrhead CS Environment Canada[3]
St. Albert weather station: St Albert Research Station[3]
Indian Head weather station: Indian Head AAFC

**Table 4-3**. Analysis of variance for effect of year, plant growth regulator and N rate treatment on oat height (cm), grain yield (kg ha$^{-1}$) and lodging at Barrhead, St. Albert and Indian Head locations.

| Effect/contrasts | Yield (kg ha$^{-1}$) | | | Height (cm) | | | Lodging | | |
|---|---|---|---|---|---|---|---|---|---|
| | Barrhead | St. Albert | Indian Head | Barrhead | St. Albert | Indian Head | Barrhead | St. Albert | Indian Head |
| Year | <0.0001 | <0.0001 | 0.5638 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| PGR rate | 0.5448 | 0.0372 | 0.1531 | <0.0001 | <0.0001 | <0.0001 | 0.0929 | 0.0013 | <0.0001 |
| N rate | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| PGR x N | 0.1853 | 0.6858 | 0.0133 | 0.1125 | 0.4785 | 0.1352 | 0.4620 | 0.0294 | 0.0003 |
| PGR x Year | 0.0143 | 0.0033 | 0.4829 | <0.0001 | 0.0075 | 0.0009 | 0.0232 | <0.0001 | <0.0001 |
| N x Year | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0109 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| PGR x N x Year | 0.8988 | 0.5055 | <0.0001 | 0.5380 | 0.0094 | 0.2089 | 0.5830 | 0.1651 | <0.0001 |
| PGR linear | 0.2200 | 0.0289 | 0.1810 | <0.0001 | <0.0001 | <0.0001 | 0.8415 | 0.0004 | 0.0004 |
| PGR quadratic | 0.2820 | 0.9080 | 0.1220 | 0.1060 | 0.1980 | 0.5645 | 0.0335 | 0.8200 | 0.4710 |
| N linear | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0003 | <0.0001 | <0.0001 |
| N quadratic | 0.0074 | 0.1544 | 0.0013 | 0.0015 | <0.0001 | <0.0001 | 0.4121 | 0.5009 | 0.0779 |

**Table 4-4**. Analysis of variance for effect of year, plant growth regulator and N rate treatment on oat test weight (kg/hL), TKW(g) and plump kernel (%) at Barrhead, St. Albert and Indian Head locations.

| Effect/contrasts | Test Weight (kg/hL) | | | TKW(g) | | | Plump kernel (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Barrhead | St. Albert | Indian Head | Barrhead | St. Albert | Indian Head | Barrhead | St. Albert | Indian Head |
| Year | <0.0001 | <0.0001 | 0.0006 | 0.0044 | 0.0214 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| PGR rate | 0.7002 | 0.8214 | 0.0075 | 0.2547 | 0.03492 | 0.1339 | 0.0306 | <0.0001 | <0.0001 |
| N rate | 0.0229 | 0.0119 | <0.0001 | 0.9322 | 0.2167 | 0.1356 | 0.0044 | <0.0001 | <0.0001 |
| PGR x N | 0.1476 | 0.1353 | 0.2941 | 0.7074 | 0.0043 | 0.0073 | 0.0161 | 0.6047 | 0.0047 |
| PGR X Year | 0.3115 | 0.3155 | 0.0108 | 0.1811 | 0.0016 | 0.6133 | 0.0009 | 0.0037 | <0.0001 |
| N x Year | 0.0729 | 0.0499 | <0.0001 | 0.0740 | 0.3049 | 0.0003 | <0.0001 | <0.0001 | <0.0001 |
| PGR x N X Year | 0.0848 | 0.708 | 0.0004 | 0.8430 | 0.0646 | 0.3099 | <0.0001 | 0.1050 | 0.0178 |
| PGR linear | 0.7680 | 0.5568 | 0.0449 | 0.1462 | 0.2010 | 0.8334 | 0.1397 | 0.0510 | <0.0001 |
| PGR quadratic | 0.1060 | 0.9930 | 0.0218 | 0.4990 | 0.5650 | 0.0429 | 0.0537 | 0.0026 | 0.3031 |
| N linear | 0.0084 | 0.0101 | <0.0001 | 0.7164 | 0.0647 | 0.2024 | <0.0001 | <0.0001 | 0.0032 |
| N quadratic | 0.4392 | 0.0246 | 0.1474 | 0.9463 | 0.8990 | 0.3790 | 0.6650 | 0.0005 | <0.0001 |

**Table 4-5**. The effect of year, plant growth regulator and nitrogen rate on agronomic and grain quality parameters at Barrhead.

| | | Yield (kg $ha^{-1}$) | Height (cm) | Lodging (1-5) | Test Weight (kg/hL) | TKW(g) | Plump kernel (%) |
|---|---|---|---|---|---|---|---|
| Year | 2014 | 6403b | 107.5b | 1.11a | 46.6a | 29.4b | 86.0a |
| | 2015 | 3116a | 63.2a | 1.00a | 47.1a | 30.2a | 86.3a |
| | 2016 | 9005c | 123.2c | 3.56b | 52.9b | 28.7b | 82.5b |
| PGR rate | 0 | 6109a | 100.5b | 1.83a | 48.7a | 29.9a | 85.2a |
| | 70 | 6215a | 99.0b | 1.95a | 49.0a | 29.4a | 85.8a |
| | 100 | 6220a | 97.7ab | 1.95a | 48.9a | 29.0a | 84.8a |
| | 130 | 6153a | 94.7a | 1.80a | 48.9a | 29.3a | 84.0a |
| N rate | 5 | 5315a | 92.0a | 1.64a | 49.4a | 29.4a | 86.0b |
| | 50 | 6163b | 98.7b | 1.66a | 48.9ab | 29.7a | 86.1b |
| | 100 | 6573c | 100.3b | 1.99ab | 49.0ab | 29.1a | 84.1a |
| | 150 | 6646c | 100.8b | 2.25b | 48.0a | 29.4a | 83.7a |
| | SE | 189 | 1.93 | 0.09 | 0.23 | 0.18 | 0.27 |

Significance: a,b,c means within a column followed by different letters are significantly different by Tukey's t test ($P \leq 0.05$).

**Table 4-6**. The effect of year, plant growth regulator and nitrogen rate on agronomic and grain quality parameters at St. Albert.

| | | Yield (kg $ha^{-1}$) | Height (cm) | Lodging (1-5) | Test Weight (kg/hL) | TKW(g) | Plump kernel (%) |
|---|---|---|---|---|---|---|---|
| Year | 2014 | 6136b | 106.5c | 1.00a | 50.7a | 32.6b | 84.5a |
| | 2015 | 4419a | 75.9a | 1.00a | 50.3a | 32.5b | 84.8a |
| | 2016 | 4834a | 100.5b | 2.40b | 53.4b | 31.7a | 88.3b |
| PGR rate | 0 | 4922a | 99.7c | 1.63b | 51.3a | 32.3a | 86.2ab |
| | 70 | 5236a | 95.7bc | 1.60ab | 51.2a | 32.5a | 87.2b |
| | 100 | 5175a | 91.8ab | 1.38a | 51.9a | 31.1a | 85.8ab |
| | 130 | 5184a | 90.0a | 1.43ab | 51.5a | 33.3a | 84.3a |
| N rate | 5 | 3739a | 85.5a | 1.05a | 52.5b | 32.6a | 91.6c |
| | 50 | 5790b | 92.7b | 1.38b | 51.4ab | 32.8a | 85.4b |
| | 100 | 6306bc | 95.6b | 1.63bc | 50.4a | 31.8a | 83.5ab |
| | 150 | 6937c | 95.5b | 1.79c | 51.6ab | 31.9a | 82.9a |
| | SE | 83.7 | 1.09 | 0.06 | 0.28 | 0.14 | 0.38 |

Significance: a,b,c means within a column followed by different letters are significantly different by Tukey's t test ($P \leq 0.05$).

**Table 4-7**. The effect of year, plant growth regulator and nitrogen rate on agronomic and grain quality parameters at Indian Head.

| | | Yield (kg ha$^{-1}$) | Height (cm) | Lodging (1-5) | Test Weight (kg/hL) | TKW(g) | Plump kernel (%) |
|---|---|---|---|---|---|---|---|
| Year | 2014 | 3724a | 82.8b | 2.53b | 51.3a | 26.6a | 73.1a |
| | 2015 | 3936a | 70.8a | 1.00a | 51.7a | 25.7a | 70.4a |
| | 2016 | 4080a | 89.9c | 1.26a | 53.3b | 31.9b | 90.2b |
| PGR rate | 0 | 3959a | 89.3c | 1.90b | 52.3b | 28.6a | 82.3c |
| | 70 | 4021a | 82.7b | 1.70ab | 52.3b | 28.0a | 77.7b |
| | 100 | 3900a | 77.8a | 1.47ab | 52.4b | 28.3a | 76.5ab |
| | 130 | 3774a | 74.8a | 1.31a | 51.5a | 28.7a | 75.2a |
| N rate | 5 | 2925a | 69.8a | 1.00a | 52.8a | 28.5a | 88.7b |
| | 50 | 3754b | 81.4b | 1.54b | 52.4a | 28.1a | 74.0a |
| | 100 | 4462c | 87.4c | 1.93c | 52.2a | 27.5a | 74.6a |
| | 150 | 4463c | 86.1c | 1.92c | 51.1b | 28.2a | 74.3a |
| | SE | 74.2 | 1.01 | 0.07 | 0.11 | 0.24 | 0.92 |

Significance: a,b,c means within a column followed by different letters are significantly different by Tukey's t test ($P \leq 0.05$).

**Table 4-8**. Regression formulas of the oat yield

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | Level | Yield (kg ha$^{-1}$) | | |
| PGR | | ns | Y=4766.556+2.688x | ns |
| N rate | | $Y=5221.39 + 22.66x - 0.088x^2$ | Y=4130.573+10.997x | $Y=2804.7167+25.1320x-0.0932x^2$ |
| PGR x Year | 2014 | ns | ns | ns |
| | 2015 | ns | ns | ns |
| | 2016 | Y=8757.187+3.305x | Y=4193.662+8.596x | ns |
| N x Year | 2014 | $Y=4813.138+35.854x-0.131x^2$ | $Y=3685.7042+42.7907x-0.1384x^2$ | $Y=2598.3018+27.9088x-0.1144x^2$ |
| | 2015 | Y=3010.738+1.402x | ns | Y=3695.989+5.062x |
| | 2016 | $Y=7785.802+32.695x-0.145x^2$ | Y=4031.578+10.581x | $Y=2419.5767+29.2506-0.0819x^2$ |
| PGR x N rate | 5 | ns | ns | ns |
| | 50 | ns | ns | ns |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | $Y=4442.2747+17.3678x-0.1634x^2$ |

**Table 4-9**. Regression formulas of the oat Height

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | Level | Height (cm) | | |
| PGR | | y=101.19-0.042x | Y=97.232-0.0731x | Y=89.650-0.1130x |
| N rate | | $Y=91.611+0.161x-0.0007x^2$ | $Y=83.698+0.2078x-0.0009x^2$ | $Y=68.1913+0.3376x-0.0015x^2$ |
| PGR x Year | 2014 | Y=110.02-0.033x | $Y=110.4-0.0140x+0.0005x^2$ | $Y=91.5687-0.0443x-0.0007x^2$ |
| | 2015 | ns | Y=80.341-0.0889x | Y=82.4964-0.1551x |
| | 2016 | $Y=128.5+0.045X-0.0011x^2$ | $Y=100.70+0.0487x-0.00088x^2$ | Y=93.8845-0.0538x |
| N x Year | 2014 | $Y=97.613+0.257x-0.0011x^2$ | $Y=94.9824+0.2139x-0.0008x^2$ | $Y=69.5786+0.3227x-0.0013x^2$ |
| | 2015 | ns | $Y=68.4094+0.1561x-0.00076x^2$ | $Y=62.8434+0.2506x-0.0013x^2$ |
| | 2016 | $Y=114.4+0.206x-0.00079x^2$ | $Y=87.9022+0.2502x-0.0011x^2$ | $Y=72.0268+0.4495x-0.0019x^2$ |
| PGR x N rate | 5 | ns | ns | ns |
| | 50 | ns | ns | ns |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | ns |

**Table 4-10**. Regression formulas of the oat Lodging

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | Level | Lodging score (1-5) | | |
| PGR | | ns | Y=1.9501-0.0045x | Y=1.6230-0.0021x |
| N rate | | Y=1.548+0.0045x | Y=1.1042+0.0065x | Y=1.0673+0.0052x |
| PGR x Year | 2014 | ns | Y=3.4183-0.0118x | Y=1.000+0.0001x |
| | 2015 | ns | ns | Y=1.1208-0.0011x |
| | 2016 | $Y=3.308+0.0134x-0.00009x^2$ | Y=1.4174-0.0020x | Y=2.7419-0.0053x |
| N x Year | 2014 | ns | $Y=0.8419+0.0371x-0.0001x^2$ | $Y=1.000-0.0001x+0.0001x^2$ |
| | 2015 | ns | ns | ns |
| | 2016 | Y=2.732+0.0109x | $Y=0.8944+0.0115x-0.0001x^2$ | $Y=0.9954+0.02635x-0.0001x^2$ |
| PGR x N rate | 5 | ns | ns | ns |
| | 50 | ns | Y=1.9718-0.0057x | ns |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | ns |

**Table 4-11**. Regression formulas of the oat Test weight

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | Level | Test weight (kg/hL) | | |
| PGR | | ns | ns | $Y=52.350+0.0106x-0.0001x^2$ |
| N rate | | $Y=49.5360-0.0081x$ | $Y=52.88-0.0487x+0.0003x^2$ | $Y=52.9603-0.0107x$ |
| PGR x Year | 2014 | ns | ns | $Y=51.81+0.01475x-0.0001x^2$ |
| | 2015 | ns | ns | $Y=52.2417-0.0064x$ |
| | 2016 | ns | ns | ns |
| N x Year | 2014 | ns | $Y=51.5681-0.0110x$ | $Y=52.5077-0.01522x$ |
| | 2015 | ns | $Y=52.8400-0.1191x+0.0007x^2$ | $Y=51.820+0.02510x-0.0002x^2$ |
| | 2016 | ns | $Y=54.044-0.0080x$ | $Y=54.220-0.02532x+0.0001x^2$ |
| PGR x N rate | 5 | ns | ns | ns |
| | 50 | ns | ns | ns |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | ns |

**Table 4-12**. Regression formulas of the oat TKW

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | Level | | TKW (g 1000 kernel$^{-1}$) | |
| PGR | | ns | ns | ns |
| N rate | | ns | ns | Y=2804.7167+25.1320x-0.0932x2 |
| PGR x Year | 2014 | ns | Y=32.2946-0.0226x+0.0002x2 | ns |
| | 2015 | ns | Y=32.2822-0.0198x+0.0002x2 | ns |
| | 2016 | ns | ns | ns |
| N x Year | 2014 | ns | ns | Y=2598.3018+27.9088x-0.1144x2 |
| | 2015 | ns | ns | Y=3695.989+5.062x |
| | 2016 | ns | ns | Y=2419.5767+29.2506-0.0819x2 |
| PGR x N rate | 5 | ns | Y=31.2780+0.0182x | ns |
| | 50 | ns | ns | ns |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | Y=4442.2747+17.3678x-0.1634x2 |

**Table 4-13**. Regression formulas of the oat Plump kernels

| | | Barrhead | St. Albert | Indian Head |
|---|---|---|---|---|
| Effects | | Plump kernels (%) | | |
| PGR | | ns | $Y=86.1700+0.0472x-0.0005x^2$ | $Y=82.1569-0.0559x$ |
| N rate | | $Y=86.4613-0.0194x$ | $Y=92.2043-0.1562x+0.0006x^2$ | $Y=89.3412-0.3298x+0.0016x^2$ |
| PGR x Year | 2014 | ns | $Y=83.6956+0.1018x-0.0008x^2$ | $Y=77.6020-0.0600x$ |
| | 2015 | $Y=87.3264-0.0124x$ | $Y=84.9701+0.0835x-0.0008x^2$ | $Y=77.1452-0.0890x$ |
| | 2016 | $Y=81.2808+0.1237x-0.0010x^2$ | $Y=89.5700-0.0161x$ | $Y=91.5795-0.0170x$ |
| N x Year | 2014 | ns | $Y=93.7386-0.2458x+0.0011x^2$ | $Y=89.5065-0.4765x+0.0023x^2$ |
| | 2015 | $Y=86.57+0.0176x-0.00018x^2$ | $Y=93.2213-0.2118x+0.0009x^2$ | $Y=86.1518-0.4587x+0.0022x^2$ |
| | 2016 | $Y=85.5-0.0393x$ | $Y=89.8361-0.0194x$ | $Y=92.3300-0.05072x+0.0002x^2$ |
| PGR x N rate | 5 | ns | ns | $Y=92.3027-0.0478x$ |
| | 50 | ns | ns | $Y=81.0438-0.0930x$ |
| | 100 | ns | ns | ns |
| | 150 | ns | ns | ns |

Table 4-14. Effect of growing conditions on yields with TE application.

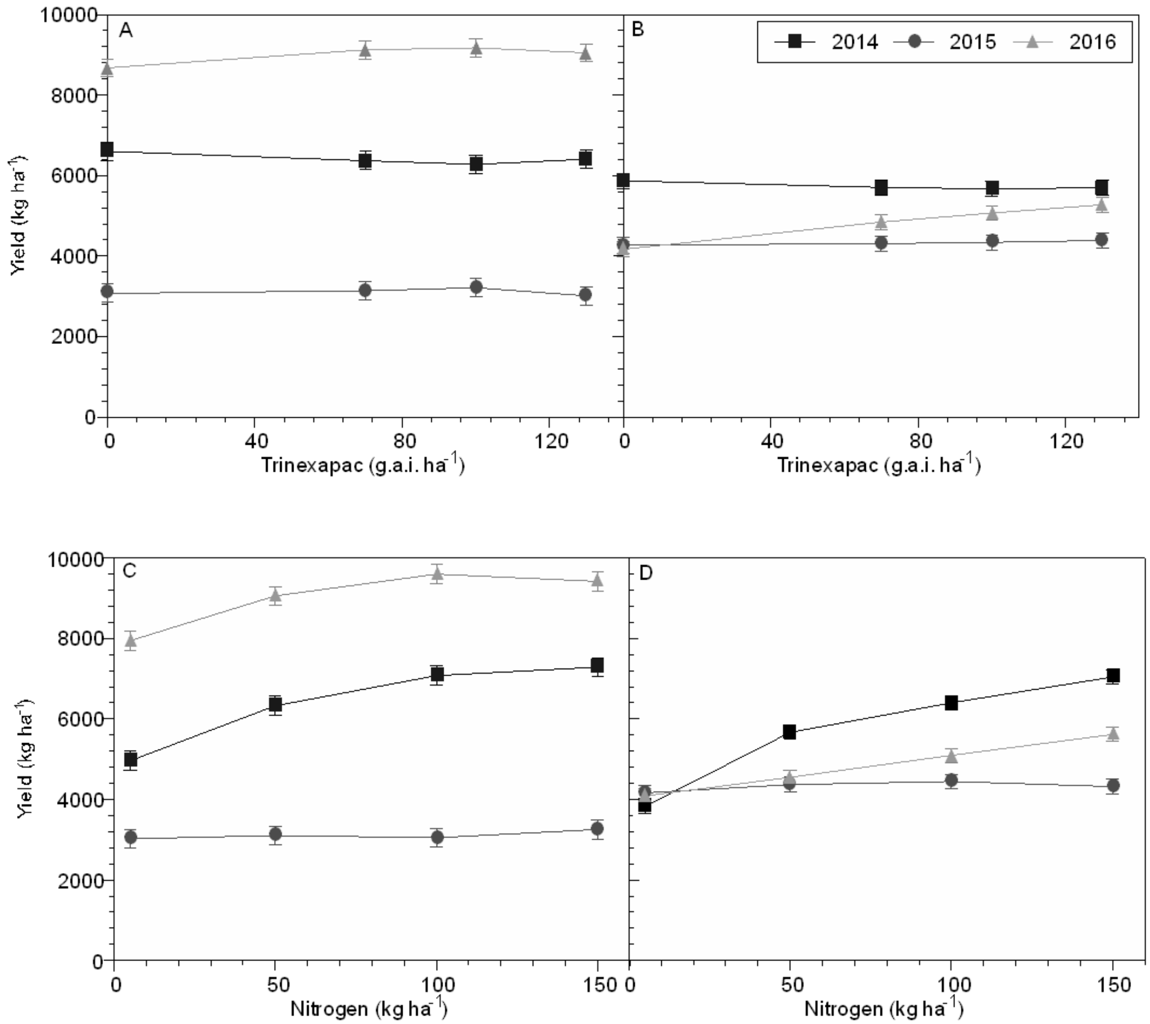
| Normal year | Dry year | Wet year |
| --- | --- | --- |
| 2014 Barrhead | 2015 Indianhead | 2016 Barrhead |
| 2014 St. Albert | | 2016 St. Albert |
| 2014 Indianhead | | |
| 2016 Indianhead | | |
| 2015 Barrhead | | |
| 2015 St. Albert | | |

Normal - No yield response

Dry - Yield decrease

Wet - Yield increase

| Table 4-15. Pesticides applied to plots at Barrhead, St. Albert and Indian Head from 2014-2016 | | | |
|---|---|---|---|
| Site | Chemical | Application rate | Target Pest |
| | **Herbicides:** | | |
| Barrhead | Spectrum A<br>Spectrum B | 0.1 L $ha^{-1}$<br>1.48 L $ha^{-1}$ | lamb' quarters |
| St. Albert | Frontline XL | 1.24 L $ha^{-1}$ | Wild buckwheat |
| Indian Head | Prestige XC A<br>Prestige XC B | 0.4 L $ha^{-1}$<br>2 L $ha^{-1}$ | redroot pigweed<br>Canada thistle |
| | | | |
| | **Fungicides:** | | |
| Barrhead | Caramba | 1 L $ha^{-1}$ | crown rust |
| St. Albert | Headline | 0.3 L $ha^{-1}$ | crown rust |
| Indian Head | n/a | n/a | n/a |
| | | | |
| | **Dessicants:** | | |
| Barrhead | Reglone | 1.7 L $ha^{-1}$ | n/a |
| St. Albert | Reglone | 1.7 L $ha^{-1}$ | n/a |
| Indian Head | n/a | n/a | n/a |


A
B
C
D
2014
2015
2016
Yield (kg ha-1)
Trinexapac (g.a.i. ha-1)
Nitrogen (kg ha-1)
0
2000
4000
6000
8000
10000
0
40
80
120
0
50
100
150

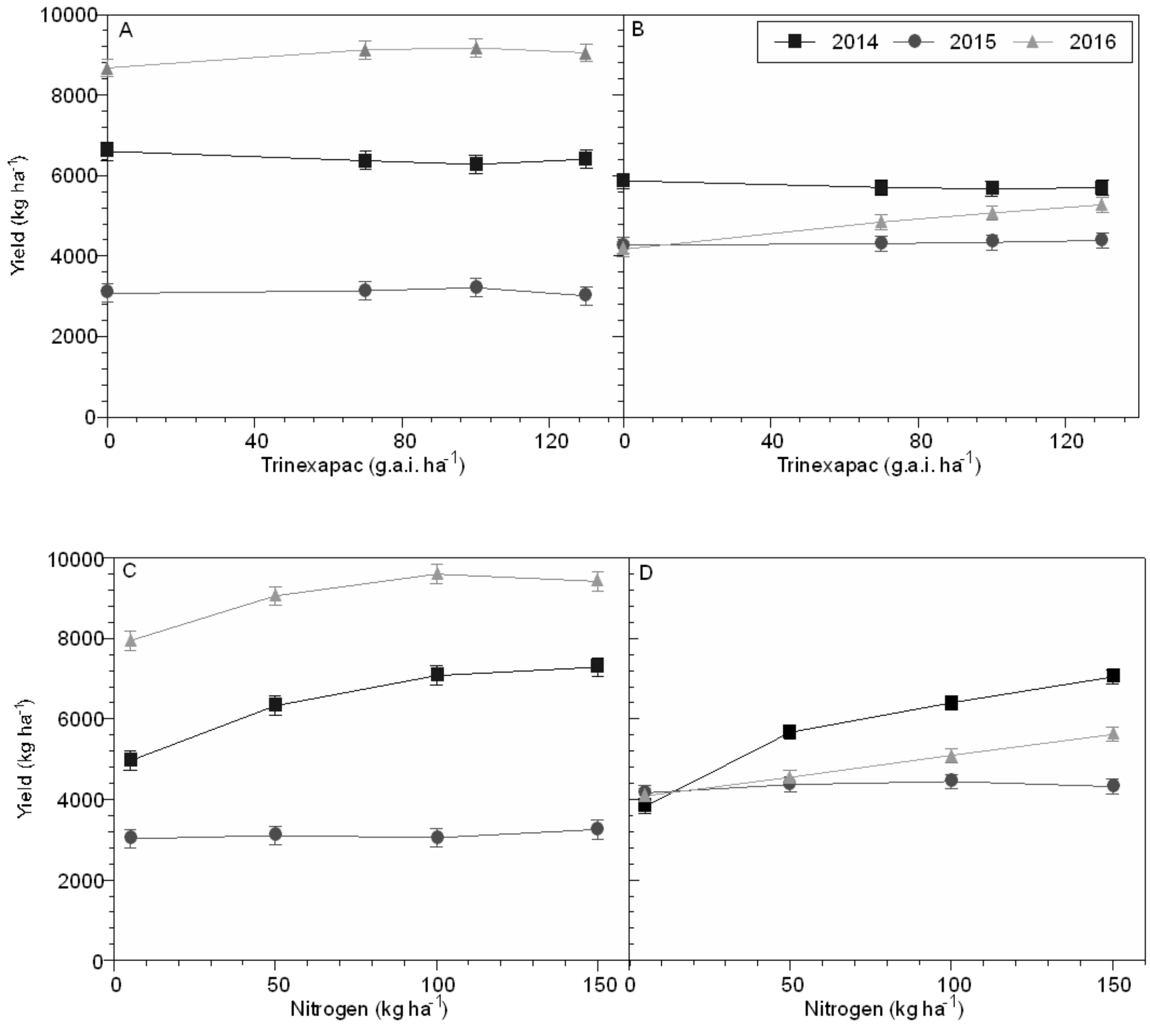



Figure 4-1. Oat grain yield least squares means affected by PGR, nitrogen rates and year of cultivation (error bars indicate SE). **A**. Oat grain yield response to trinexapac-ethyl and year of cultivation at Barrhead. **B**. Oat grain yield response to trinexapac-ethyl and year of cultivation at St. Albert. **C**. Oat grain yield response to nitrogen and year of cultivation at Barrhead. **D**. Oat grain yield response to nitrogen and year of cultivation at St. Albert.

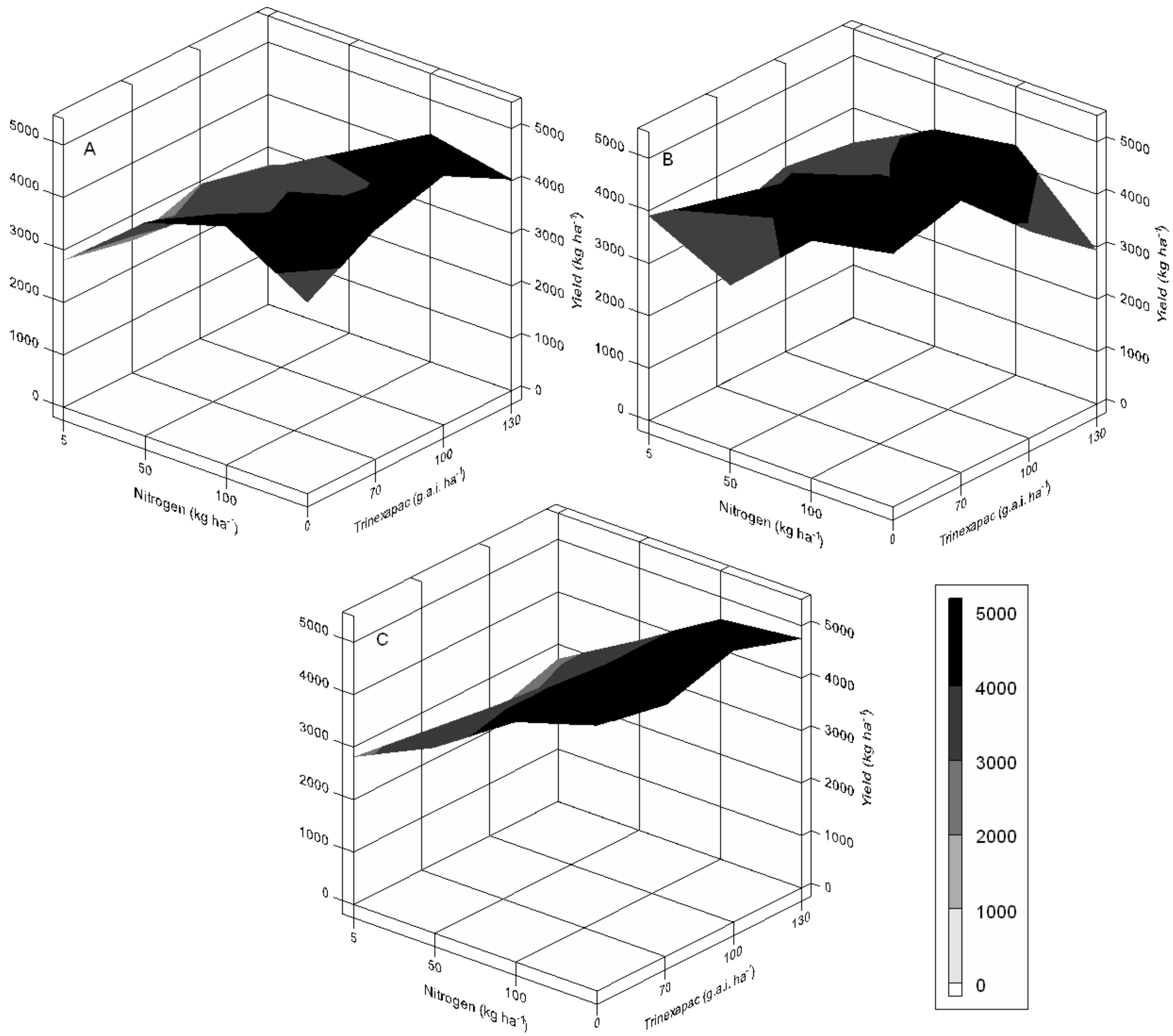



Figure 4-2. Oat grain yield least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at Indian Head. **A**. Oat grain yield response to trinexapac-ethyl and nitrogen in 2014. **B**. Oat grain yield response to trinexapac-ethyl and nitrogen in 2015. **C**. Oat grain yield response to trinexapac-ethyl and nitrogen in 2016.

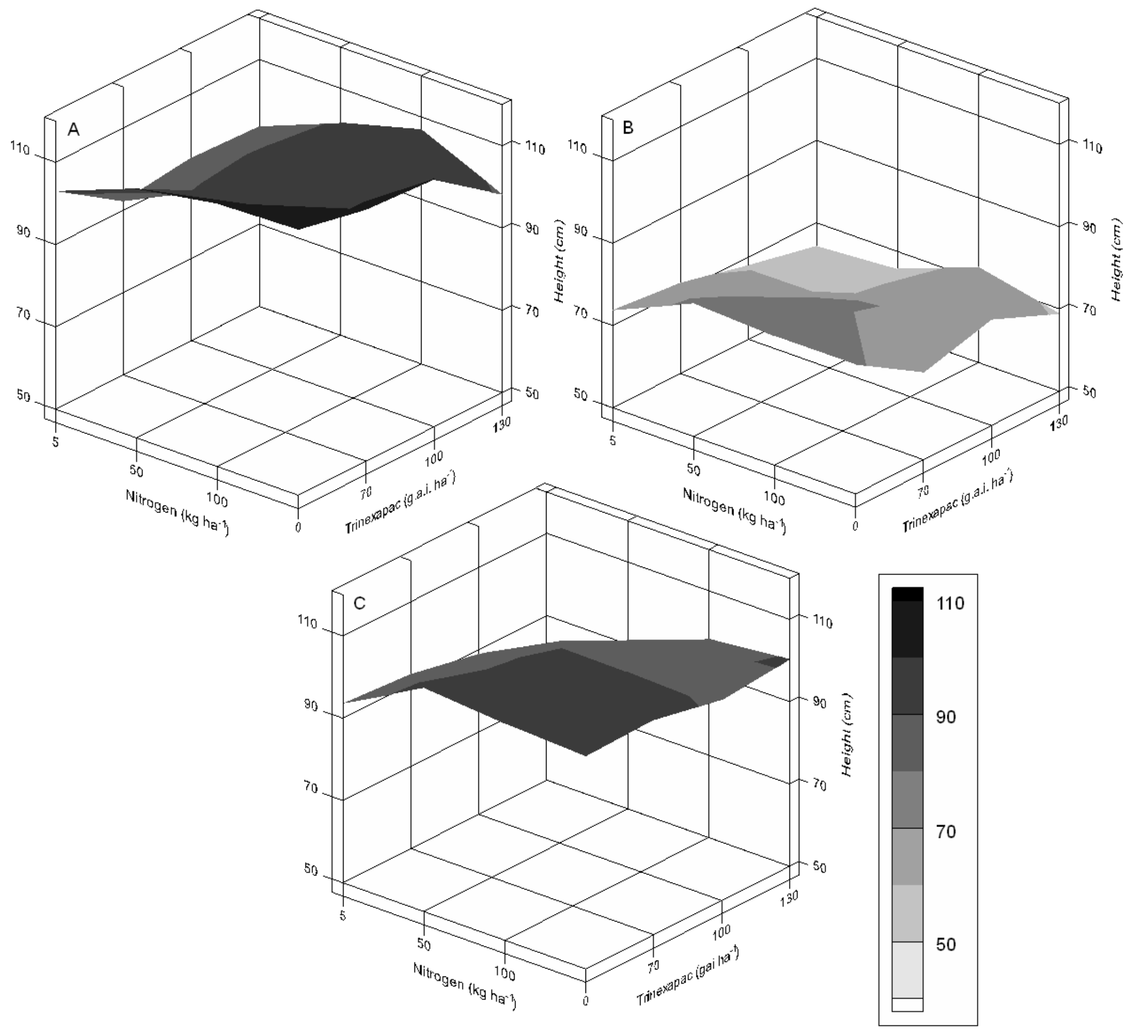



Figure 4-3. Plant height least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at St Albert. **A**. Height response to trinexapac-ethyl and nitrogen in 2014. **B**. Height response to trinexapac-ethyl and nitrogen in 2015. **C**. Height response to trinexapac-ethyl and nitrogen in 2016.

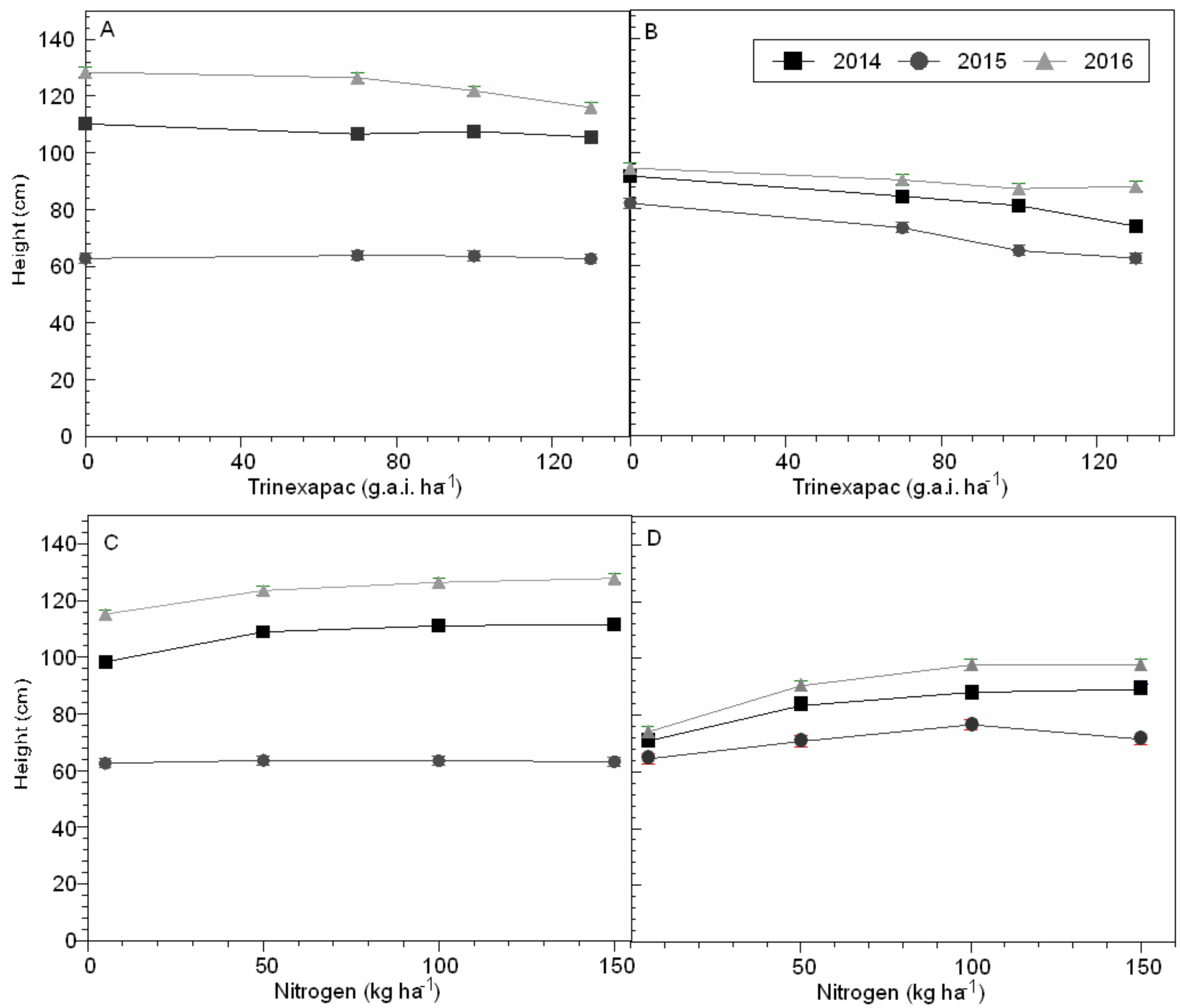



Figure 4-4. Plant height least squares means affected by PGR, nitrogen rates and year of cultivation (error bars indicate SE). **A**. Height response to trinexapac-ethyl and year of cultivation at Barrhead. **B**. Height response to trinexapac-ethyl and year of cultivation at Indian Head. **C**. Height response to nitrogen and year of cultivation at Barrhead. **D**. Height response to nitrogen and year of cultivation at Indian Head.

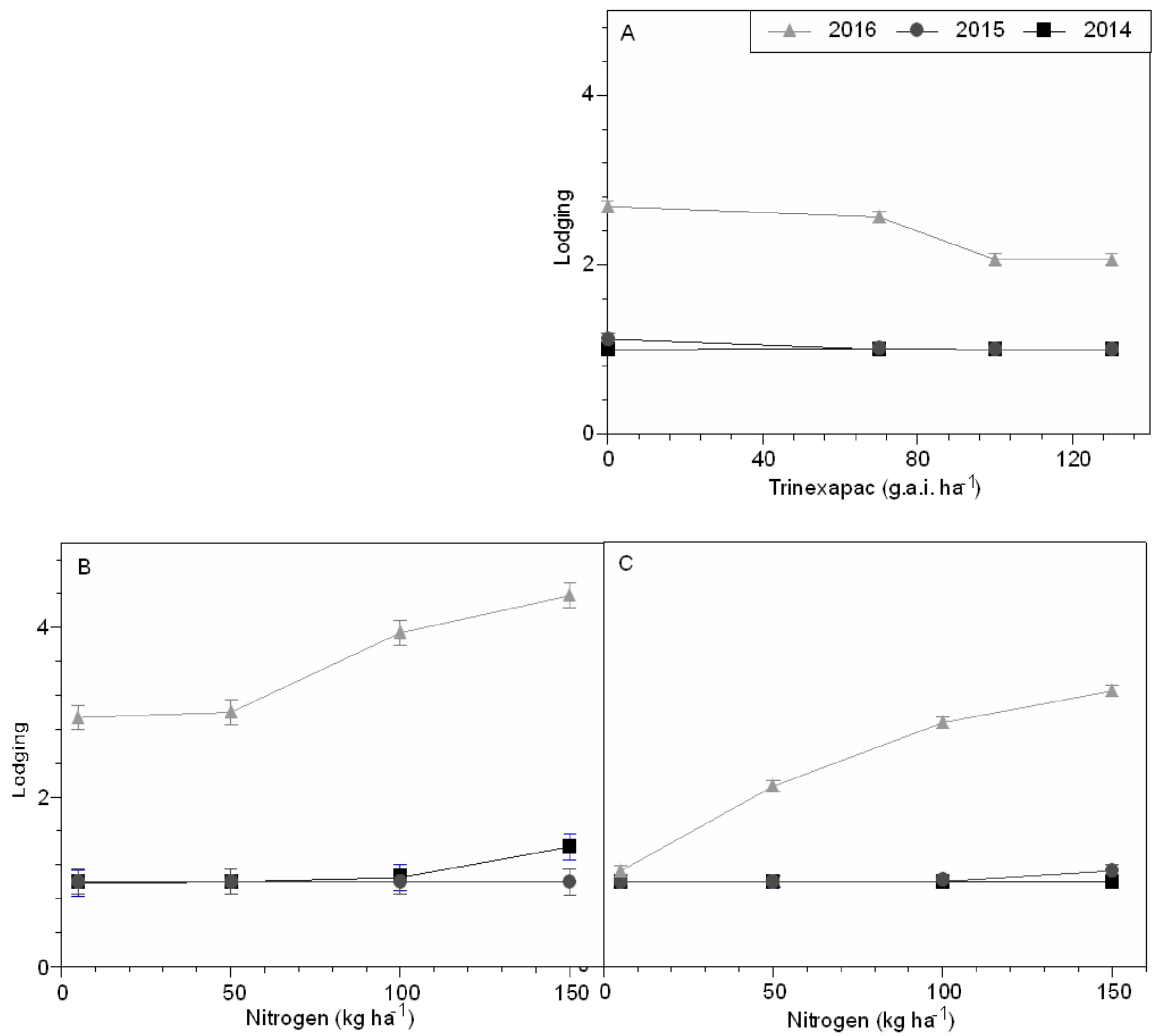



Figure 4-5. Lodging means affected by PGR and year of cultivation; nitrogen rates and year of cultivation (error bars indicate SE). **A**. Lodging response to trinexapac-ethyl and year of cultivation at St. Albert. **B**. Lodging response to nitrogen and year of cultivation at Barrhead. **C**. Lodging response to nitrogen and year of cultivation at St. Albert.

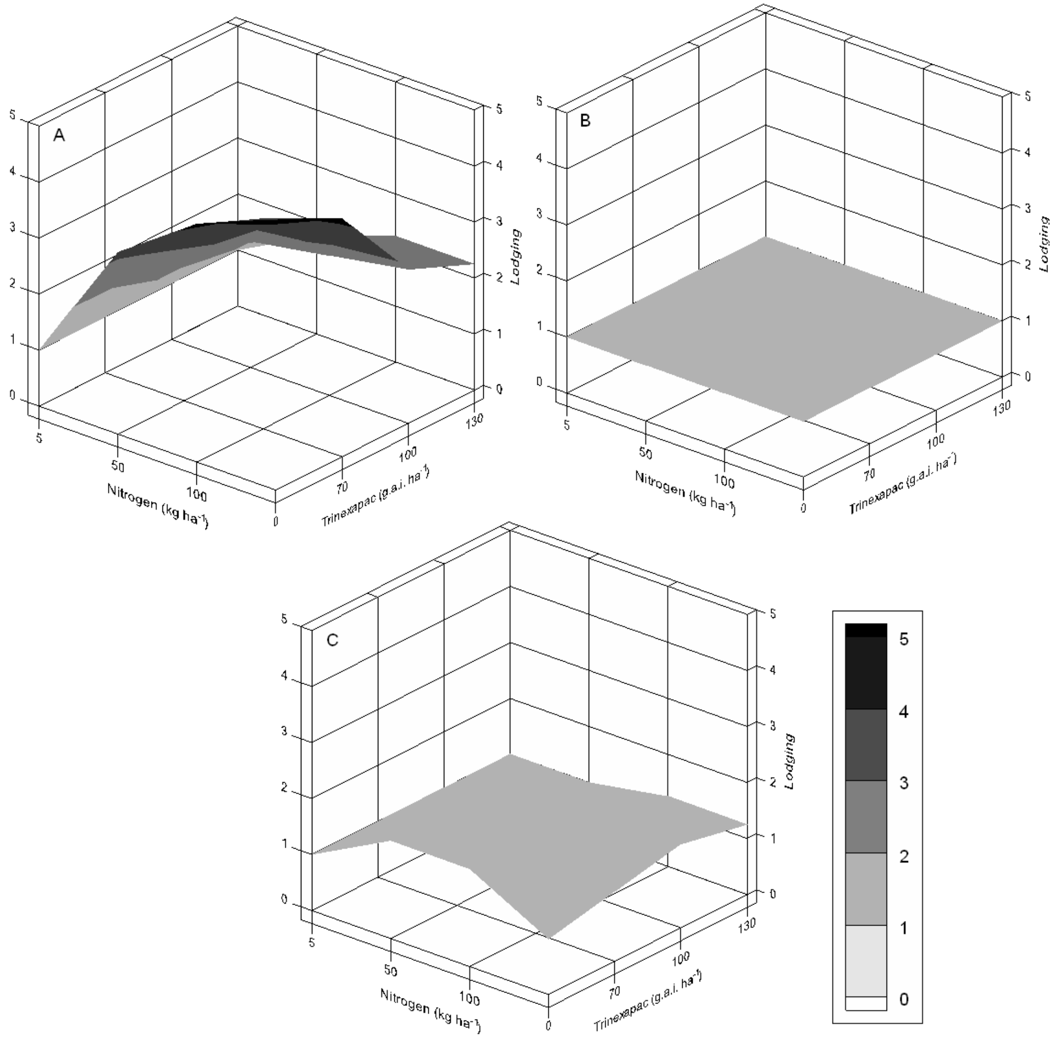



Figure 4-6. Lodging least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at Indian Head. **A**. Lodging response to trinexapac-ethyl and nitrogen in 2014. **B**. Lodging response to trinexapac-ethyl and nitrogen in 2015. **C**. Lodging response to trinexapac-ethyl and nitrogen in 2016.

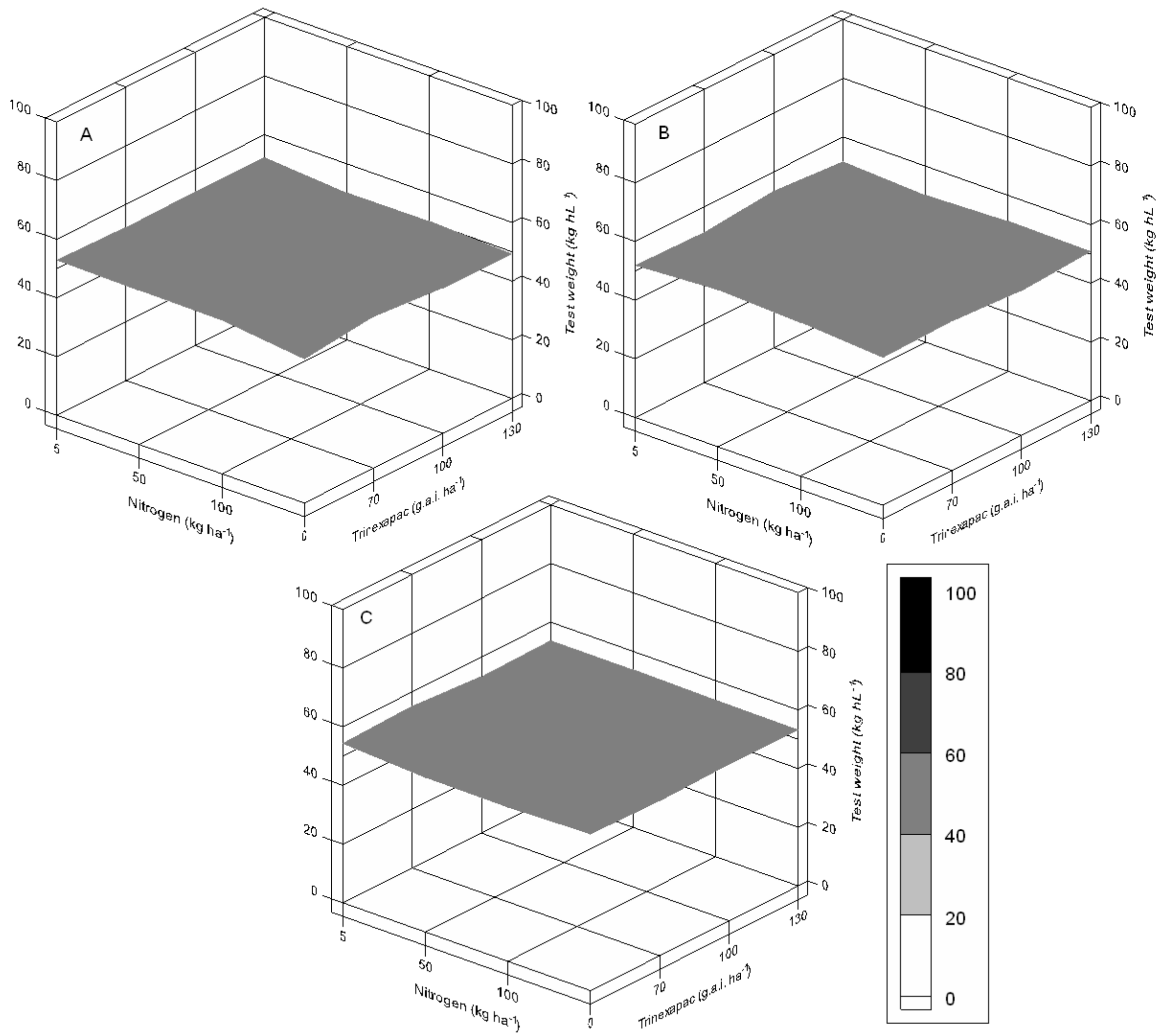



Figure 4-7. Test weight least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at Indian Head. **A**. Effect of trinexapac-ethyl and nitrogen on test weight in 2014. **B**. Effect of trinexapac-ethyl and nitrogen on test weight in 2015. **C**. Effect of trinexapac-ethyl and nitrogen on test weight in 2016.

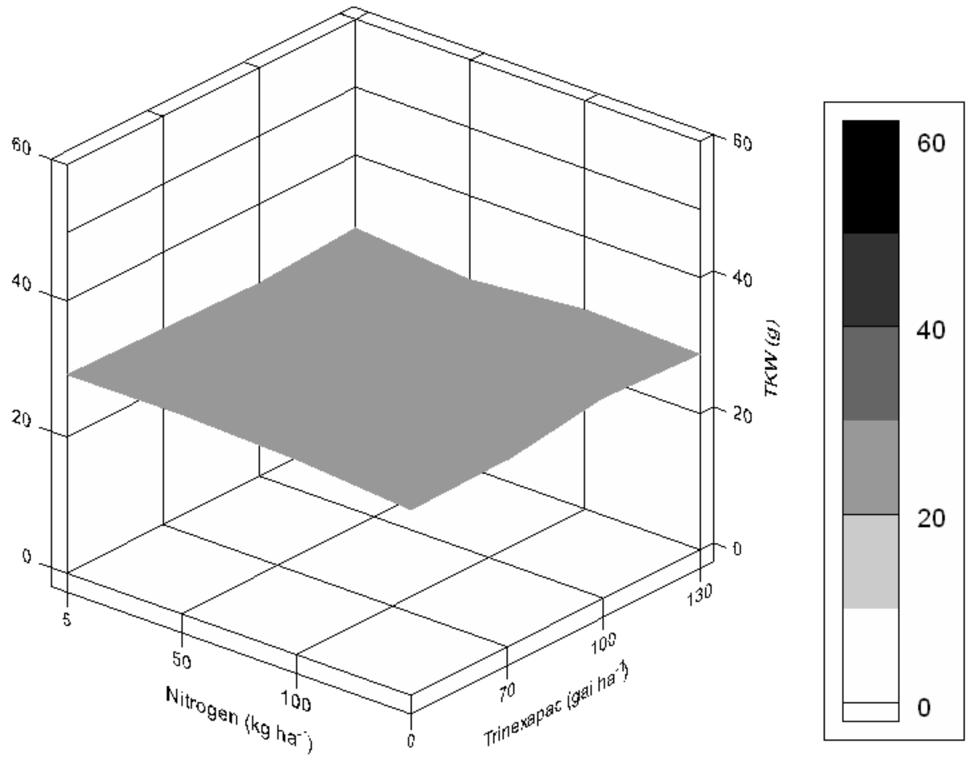



Figure 4-8. TKW least squares means affected by two-way interaction between nitrogen and PGR at Indian Head.

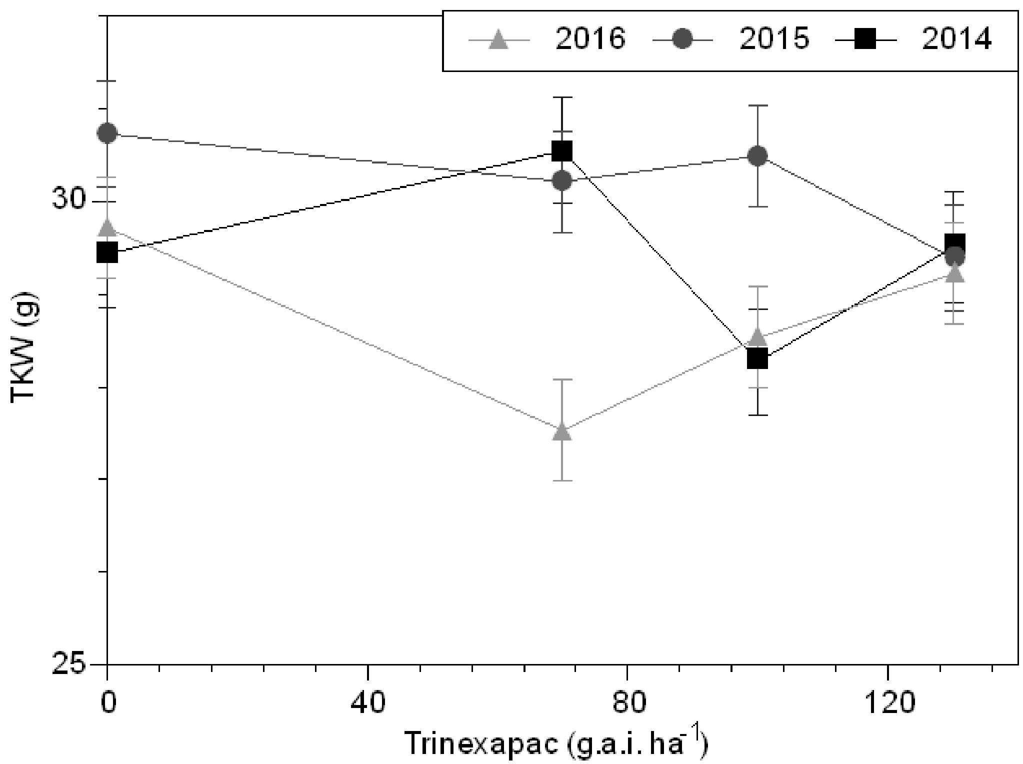



Figure 4-9. TKW least squares means affected by two-way interaction between PGR and year of cultivation at St. Albert.

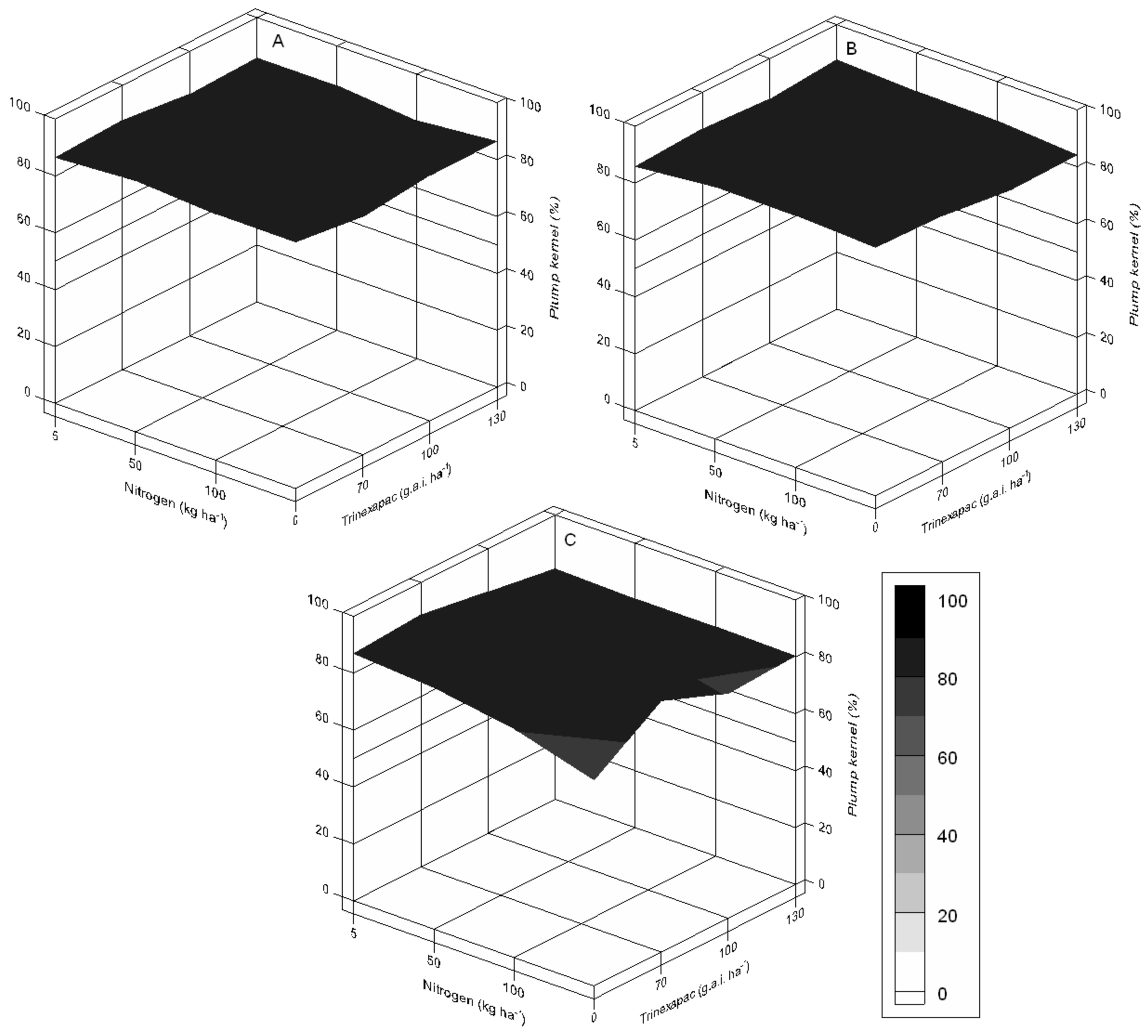



Figure 4-10. Plump least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at Barrhead. **A**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2014. **B**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2015. **C**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2016.

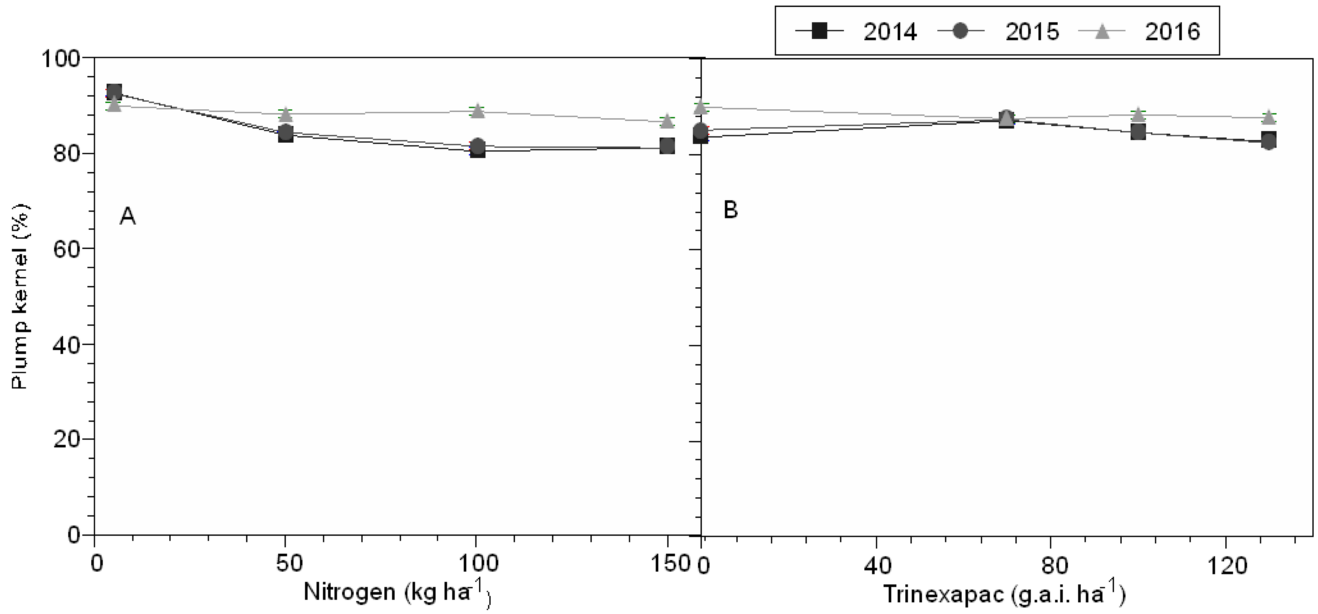



Figure 4-11. Plumps least squares means affected by PGR nitrogen rates and year of cultivation at St. Albert (error bars indicate SE). **A**. Effect of nitrogen and year of cultivation on plump kernels. **B**. Effect of trinexapac-ethyl and year of cultivation on plump kernels.

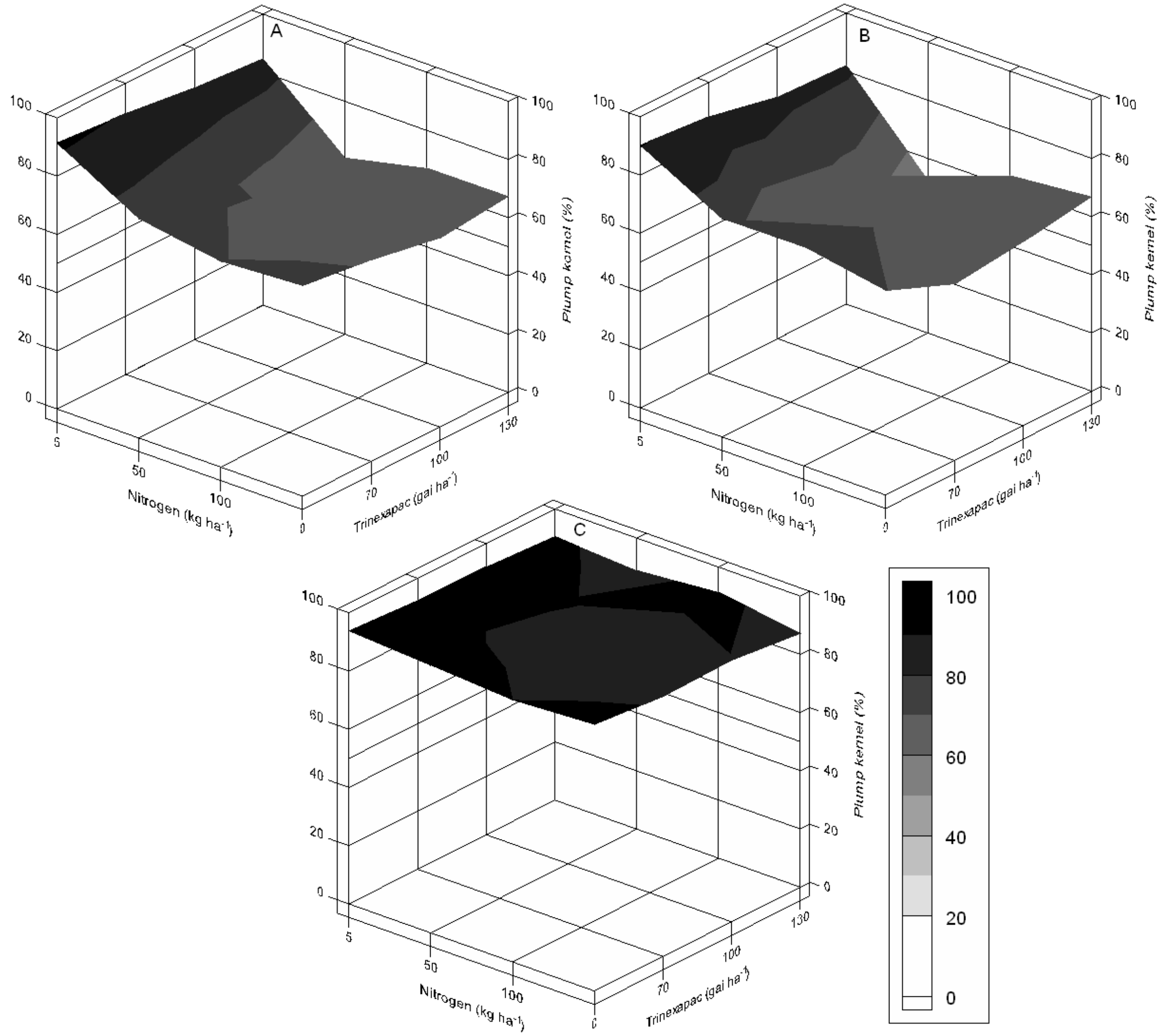



Figure 4-12. Plump least squares means affected by three-way interaction between PGR, nitrogen rates and year of cultivation at Indian Head. **A**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2014. **B**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2015. **C**. Effect of trinexapac-ethyl and nitrogen on plump kernels in 2016.

# Chapter Five: General Discussion and Conclusions

## 5.1. Summary of Results

Although Alberta is one of Western Canada's principal oat producing regions, producers have been relying on traditional agronomic information without the benefit of local recommendations. For this reason, as well as the recent advances in high β-glucan oat genotypes, up to date agronomic information was needed for Alberta and Saskatchewan producers. This study determined the most important agronomic parameters for oat in Alberta and Saskatchewan, thus ensuring the most profitable oat crop with high yields and milling grades. This study determined that cultivar and nitrogen fertilizer have implications on oat yield and quality in Central Alberta. Increasing nitrogen fertilizer levels did not improve milling quality. Canadian Oat Milling Limited has raw oat grade specifications based on parameters they measure and is principally driven by their primary end use market. Normally, milling quality oats attract a premium price relative to lower-quality feed oats, and at times, a premium over the price of high quality feed oats for the race horse market. Some of the crucial factors in determining the quality of oats include test weight, plump and thin kernels. In order to meet Health Canada's "Heart Healthy" claim oat products must have a minimum of 10% dietary fibre, a minimum of 4% β-glucans, and a maximum of 6% fat. Millers prefer oats with test weights of 54 kg $hL^{-1}$ or more with a \$3.0/MT deduction for 53-54 kg $hL^{-1,}$ and may be willing to pay premiums for heavier test weights or, conversely, accept oats weighing slightly less at a price discount. Oat with test weight less than 53 kg $hL^{-1}$ is rejected. Also, a maximum of 7% thin seed is acceptable with a \$1.5/MT deduction for each 1.0% over 7.0%; oat with thin kernels more than 10% is rejected. A minimum of 70% plump seed is acceptable on bid basis, with a price dockage on plump kernels below 90%. However, plump kernels less than 70% are usually rejected. In our study none of the oat cultivars met this milling specification, with Stride oat recording highest test weight of 49 kg $hL^{-1}$ at 100 kg $ha^{-1}$

For plump kernels cultivars in this study met the minimum acceptable requirements of 70% set by Canadian Oat Milling, however percent plump kernels CDC Norseman, CDC Morrison and Stride were below 90% and as such would be discount in the current milling market. AC Morgan and Sea Biscuit were above the required 90% grade for plump kernels.

Increasing nitrogen fertilizer rates from 5 to 150 kg $ha^{-1}$ resulted in a decrease in plump kernels from 90 to 88%. At the 50 kg N $ha^{-1}$ threshold the proportion of thin kernels being produced no longer met the milling specification (10.82%). This oat would not make milling grade and as such would be rejected based on the requirements set by the Canadian Milling. Therefore, any N additions reduced grade below acceptable levels. Cultivars evaluated in this study had significantly different proportions of thin kernels ranging from 7 to 14%. AC Morgan had significantly lower thin kernels in all site years, while Stride resulted in higher thin kernels. Nitrogen fertilization can result in reduced quality typically greater number of thin kernels produced with increasing N rates, consequently the distribution of assimilates and nutrients over a greater number of kernels resulting in thin, less filled kernels.

The cultivars evaluated in this study were developed in a range of locations; AC Morgan in Alberta; CDC Sea biscuit, CDC Morrison, CDC Norseman in Saskatchewan; and Stride in Manitoba. CDC Morrison exhibited lower yield and higher β-glucan content while CDC Norseman was determined to be extremely consistent in terms of yield and quality. Nonetheless the grain yield of AC Morgan was the highest of all cultivars in this study, it is one of the best standing oat cultivars as well as high proportion of plump kernels. These results demonstrate the necessity of oat cultivar testing in regions where the cultivars will be grown. The present study confirms the excellent effects of Saskatchewan and Manitoba's oat breeding programs but also confirms the need for additional funding for ongoing agronomic management studies to provide producers with the tools they need to achieve superior quality and yield.

Grain yield tended to be highest at higher N rates. At higher N rates there was an increase in lodging and a decline in physical grain quality. Plump kernel was the grain quality parameter component that decreased as the rate of N increased. The optimum N rate will thus involve a trade-off between yield and quality. AC Morgan had the most stable, high yields of all cultivars when N rate was increased. An oat cultivar with yield and quality stability increases the probability of obtaining high yield and quality especially when cultivated under an environment with high levels of precipitation. Compared with the most widely grown cultivar AC Morgan, CDC Norseman offer the potential to increase yields, while maintaining high β-glucan content although not significant there is a 451 kg $ha^{-1}$ yield disadvantage that needs to be considered along with its lower plump kernels and higher thin kernels. We found a significant cultivar effect observed for β-glucan content. The effect of year of cultivation on β-glucan content of cultivars under investigation was not significant. Of the cultivars studied, CDC Morrison had the highest level of β-glucan content, whereas AC Morgan had the lowest. CDC Morrison and CDC Norseman consistently showed higher values of β-glucan content across the two growing locations and years of cultivation. The present study identifies cultivar selection as the major factor that can be optimized to achieve oat products with desirable nutritional profiles.

Trinexapac-ethyl reduced plant height as well the lodging of oat plants, depending on the year and growing conditions at the site. Trinexapac-ethyl application decreased grain yield at Indian Head in 2015. There were grain yield responses following PGR application at Barrhead and St Albert in 2016. In addition, PGR application had no significant effect on physical grain parameters such as test weight and thousand kernel weight but it impacted plump kernels. According to these results, the most favorable economic outcome will likely result from using a suitable PGR as a harvest management aid to prevent lodging under conditions where it represents a considerable risk. To optimize PGR use and improve crop safety, PGRs must be applied at the right growth stage, BBCH 31. Environmental conditions may have a negative impact on performance, in this regard growers and agronomists must follow label directions. More research work should be conducted to optimize the use of PGRs in western Canada.

## 5.2. Results Summarized by Research Objective

### 5.2.1. Determine the effect of oat cultivar and nitrogen fertilization on yield and quality

Enhancing the yield and profitability of central Alberta oat growers through the selection of cultivar and optimizing nitrogen fertilizer was discussed in Chapter three. A randomized complete block factorial trial was established in 2 locations. Five oat cultivars (AC Morgan, CDC Morrison, Stride, CDC Norseman and CDC Sea Biscuit) were direct seeding into canola stubble in early- to mid-May with four nitrogen rates (5, 50, 100, 150 N kg $ha^{-1}$). Grain yield, height, lodging and grain quality parameters were evaluated. Our results indicated application of nitrogen fertilizer resulted in significant increases in plant height, lodging score and grain yield. A significant decrease in percentage plump seed was observed as nitrogen fertilizer rate increased. With the exception of lodging, cultivar by N rate interaction was not significant for any of the variables investigated. The effect of year on average β-glucan content of oat was not significant. Differences in average β-glucan content of cultivars was significant. The results from this experiment indicate that cultivar selection and fertilizer management influences the ability of oat to meet specific quality parameters for the milling market. AC Morgan should be the cultivar of choice grown at 150 kg $ha^{-1}$ fertilizer rate. Also, oat breeders should target high milling quality to attract premium prices relative to lower-quality feed oats.

### 5.2.2. Determine the effect of plant growth regulator application and nitrogen fertilization on oat yield and lodging

Chapter four describes a randomized complete block factorial trial conducted over 9 site-years to investigate the influence plant growth regulator application and nitrogen fertilization on oat yield and lodging in the cultivar CDC Stride. The use of increasing rates of trinexapac-ethyl decreased linearly the height as well as the lodging of oat plants. The use of trinexapac-ethyl did not have a significant effect on the grain yield of the crop but did decrease plant height and lodging. There were significant interactions between nitrogen and year of cultivation at all sites for grain yield as well as interactions between trinexapac and year of cultivation at Barrhead and St. Albert with significant responses observed when precipitation was normal or wet.

## 5.3 Future Research

When PGRs prevent lodging or reduce its magnitude, the effect on yield, quality and easier harvesting should increase profitability. Quite a few PGR's reduce lodging by shortening crops, nonetheless there is no published evidence on their ability to strengthen the stems and anchorage in the oat crop. Future research should investigate the effect of existing registered PGR's on stem and anchorage strength as well as concentrating on discovering new growth regulating chemicals that strengthen these traits.

We have recognized the stem shortening effects of trinexapac-ethyl, however, there are a number of unanswered questions that should be researched to ensure optimum performance under western Canadian conditions.

- An in-depth study to determine the effects of PGR's on agronomic parameters of different cultivars under conditions prevalent in the Prairies. This will answer the question of why some cultivars respond to PGR treatments and others do not.
- Application of trinexapac-ethyl together with other PGR’s using rate titration to optimize crop safety and cost effectiveness.
- A study to determine if dual applications of PGRs are useful and provide better lodging control and yield benefits.
- How environmental conditions impact performance of trinexapac-ethyl?
- Do we have the correct growth stage? Would it be useful to apply trinexapac-ethyl at multiple growth stages? Is there a benefit with tank mixing trinexapac-ethyl and chlormequat chloride, as well as PGR interactions with fungicide applications?

## Bibliography

Adams, R., Kerber, E., Pfister, K., Weiler, E. 1992. Studies on the action of the new growth retardant CGA 163’935 (cimectacarb). Pages 818-827. In Progress in Plant Growth Regulation. Proceedings of the 14th International Conference on Plant Growth Substances, C. Karssen, L. Van Loon, and D. Vreugdenhill, eds. Dordrecht: Kluwer Academic Publishers.

Agriculture Financial Services Corporation - Yield Alberta 2017. [Online] Available https://static.agcanada.com/wpcontent/uploads/2017/02/YAB170227.pdf#_ga=2.89107229.762070094.1506275861-685548685.1506275861 [20 September. 2017].

Agri-Food Statistics Update 2014. Production statistics [Online] Available http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/al l/sdd15131 [14 May. 2015].

Alberta Agriculture, Food and Rural Development. 2010. Marketing Oats in Canada. [Online] Available http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sis10952 [1 Dec. 2015]

Alberta seed guide, 2016. [Online] Available: http://seed.ab.ca/variety-trials/cereals/ [7 Jan 2017].

Åman, P. and Hesselman, K. 1985. An enzymic method for analysis of total mixed-linkage β-glucans in cereal grains. J. Cereal Sci. 3: 231-237.

and grain yield of wheat in a Mediterranean environment. Aust. J. Agric.Res. 37:219-233.

Anderson, J. W., Gilinsky, N. H., Deakins, D. A., Smith, S. F., O'Neal, D. S., Dillon, D. W., Oeltgen, P. R. 1991. Lipid responses of hypercholesterolemic men to oat-bran and wheat-bran intake. Am. J. Clin. Nutr. 54: 678-683.

Anderson, W.K. 1986. Some relationships between plant population, yield components and grain yield of wheat in a Mediterranean environment. Aust. J. Agric.Res. 37:219-233.

Arf, O., Nascimento, VD, Rodrigues, RAF, Alvarez, RDCF, Gitti, DDC and Sá, MED, 2012. Use of ethyl-trinexapac in upland rice cultivars. Tropic. Agri. Res. 42:150-158.

Bates, D., Mächler, M., Bolker, B., Walker, S. 2014. Fitting linear mixed-effects models using lme4. ArXiv Preprint arXiv:1406.5823.

Berry, P.M., 1998. Predicting lodging in winter wheat (Doctoral dissertation, University of Nottingham). [Online]. Available: http://eprints.nottingham.ac.uk/13494/1/266918.pdf [4 Jan. 2015].

Berry, P.M., Spink, J.H., Griffin, J.M., Sylvester-Bradley, R., Baker, C.J., Clare, R.W. and Scott, R.K., 1998. Research to understand, predict and control factors affecting lodging in wheat. HGCA Project Report (United Kingdom).

Berry, P. M., Griffin, J. M., Sylvester-Bradley, R., Scott, R. K., Spink, J. H., Baker, C. J., and Clare, R. W. (2000). Controlling plant form through husbandry to minimise lodging in wheat. Field Crops Res. 67, 59–81.

Berry, P. M., Spink, J. H., Sterling, M., and Pickett, A. (2003). A comparison of root and stem

Berry, P., Sterling, M., Spink, J., Baker, C., Sylvester-Bradley, R., Mooney, S., Tams, A., Ennos, A. 2004. Understanding and reducing lodging in cereals. Adv. Agron. 84: 217-271.

Berry, P., Sylvester-Bradley, R., Berry, S. 2007. Ideotype design for lodging-resistant wheat. Euphytica 154: 165-179.

Berti, M., Zagonel, Jww., Fernandes, EC. 2007. Productivity of wheat cultivars as a function of trinexapac-ethyl and nitrogen rates. Scientia Agraria, 8: 127-134.

Böse, G., Graebe, J.E., Grosselindemann, E., Hedden, P., Aach, H., Schweimer, A., Sydow, S. and Lange, T., 1992. The biosynthesis of ent-kaurene in germinating seeds and the function of 2-oxoglutarate in gibberellin biosynthesis. Pages 545-554. In Progress in Plant Growth Regulation. Springer Netherlands.

Brennan, C.S. and Cleary, L.J., 2005. The potential use of cereal (1→ 3, 1→ 4)-β-D-glucans as functional food ingredients. J Cer Sci. 42:1-13.

Brinkman, M. and Rho, Y. 1984. Response of three oat cultivars to N fertilizer. Crop Sci. 24: 973-977.

Brouwer, J. and Flood, R. G. 1995. Aspects of oat physiology. Pages 177-222, In The Oat Crop. Springer Netherlands.

Brown, A. R., Morris, H. D. and Morey, D. D. 1961. Response of seven oat varieties to different levels of fertilization. Agron. J. 53: 366–369.

Browne, R.A., White, E.M. and Burke, J.I., 2003. Effect of nitrogen, seed rate and plant growth regulator (chlormequat chloride) on the grain quality of oats (Avena sativa). J. Agric. Sci. 141: 249-258.

Browne, R.A., White, E.M. and Burke, J.I., 2006. Responses of developmental yield formation processes in oats to variety, nitrogen, seed rate and plant growth regulator and their relationship to quality. J. Agric. Sci. 144: 533-545.

Brunner, B. and Freed, R. 1994. Oat grain β-glucan content as affected by nitrogen level, location, and year. Crop Sci. 34: 473-476.

Burrows, V. D. 1986. Breeding oats for food and feed: Conventional and new techniques and materials. Pages 13-46, In Oats: Chemistry and Technology. F.H Webster American Association of Cereal Chemists, St. Paul Minnesota.

Canadian Grain Commission. 1998. Official grain grading guide. Winnipeg, MB. 7.1-7.21

Cervantes-Martinez, C., Frey, K. J., White, P. J., Wesenberg, D., Holland, J. 2001. Selection for greater β-glucan content in oat grain. Crop Sci. 41(4): 1085-1091.

Chalmers, A., Dyer, C., Sylvester-Bradley, R. 1998. Effects of nitrogen fertilizer on the grain yield and quality of winter oats. J. Agric. Sci. 131: 395-407.

Clark, R.V. and Fedak, G., 1977. Effects of chlormequat on plant height, disease development and chemical constituents of cultivars of barley, oats, and wheat. Can. J. Plant Sci. 57:31-36.

Cooper, P.J.M., Gregory, P.J., Tully, D. and Harris, H.C., 1987. Improving water use efficiency of annual crops in the rainfed farming systems of West Asia and North Africa. Experimental Agriculture. 23:113-158.

Cox, W.J. and Otis, D.J., 1989. Growth and yield of winter wheat as influenced by chlormequat chloride and ethephon. Agron. J. l, 81:264-270.

Crook, M. and Ennos, A. 1995. The effect of nitrogen and growth regulators on stem and root characteristics associated with lodging in two cultivars of winter wheat. J. Exp. Bot. 46: 931-938.

Daou, C. and Zhang, H. 2012. Oat Beta-Glucan: Its role in health promotion and prevention of diseases. Comprehensive Reviews in Food Sci. and Food Safety 11: 355-365.

Davidson, M. H., Dugan, L. D., Burns, J. H., Bova, J., Story, K., Drennan, K. B. 1991. The hypocholesterolemic effects of β-glucan in oatmeal and oat bran: A dose-controlled study. Jama. 265: 1833-1839.

De, R., Giri, G., Saran, G., Singh, R., Chaturvedi, G. 1982. Modification of water balance of dryland wheat through the use of chlormequat chloride. J. Agric. Sci. 98: 593-597.

Deiss, L., Moraes, A. d., Pelissari, A., Skora Neto, F., Oliveira, E. B. d., Silva, V. P. d. 2014. Oat tillering and tiller traits under different nitrogen levels in an eucalyptus agroforestry system in subtropical Brazil. Ciência Rural 44: 71-78.

Doehlert, D. C., McMullen, M. S., Hammond, J. J. 2001. Genotypic and environmental effects on grain yield and quality of oat grown in North Dakota. Crop Sci. 41: 1066-1072.

Easson, D.L., White, E.M. and Pickles, S.J., 1993. The effects of weather, seed rate and cultivar on lodging and yield in winter wheat. Journal of Agric. Sci., 121:145-156.

Ennos, A. R. 1991. The mechanics of anchorage in wheat Triticum aestivum L.: II. anchorage of mature wheat against lodging. J. Exp. Botany. 42: 1607-1613.

Ervin, E. and Koski, A. 2001. Kentucky bluegrass growth responses to trinexapac-ethyl, traffic, and nitrogen. Crop Sci. 41: 1871-1877.

Evans, L. and Fischer, R. 1999. Yield potential: Its definition, measurement, and significance. Crop Sci. 39: 1544-1551.

FAOSTAT, 2013. Food and Agriculture Organization of the United Nations, Rome, Italy. [Online]. Available: http://apps3.fao.org/wiews/germplasm_query.htm?i_l=EN [11 May, 2015]

FAOSTAT, 2015. Food and Agriculture Organization of the United Nations, Rome, Italy. Statistics Division. [Online]. Available http://www.fao.org/3/a-i4691e.pdf [21 March, 2016] Fifth Edition. Macmillan, New York.

Forsberg, R. A. and Reeves, D. L. 1995. Agronomy of oats. Pages 223-251, In The Oat Crop. Springer Netherlands.

Frey, K. J. 1959. Yield components in oats. II. The effect of nitrogen fertilizer. Agron. J. 51: 605–608.

Ganssmann, W. and Vorwerck, K. 1995. Oat milling, processing and storage. Pages 369-408, In The Oat Crop. Welch, Robert, Springer Netherlands.

Gates, F. K. and Dobraszczyk, B. 2008. Mechanical properties of oats and oat products. Agric and Food Sci 13: 113-123.

Gianfagna, T. 1995. Natural and synthetic growth regulators and their use in horticultural and agronomic crops. Pages 751-773, In Plant hormones. Springer Netherlands.

Gilley, A. and Fletcher, R. 1997. Relative efficacy of paclobutrazol, propiconazole and tetraconazole as stress protectants in wheat seedlings. Plant Growth Regulation 21: 169-175.

Goodwin, T.W. and Mercer, E.I., 1983. Introduction to Plant Biochemistry. Pergamon Press. New York. 83.

Hamill, M. L. 2002. The effect of cultivar, seeding date, seeding rate and nitrogen fertility on oat (Avena sativa L.) yield and milling quality. M.Sc. Thesis, University of Manitoba, Winnipeg, MB.

Hawerroth, M. C., Silva, José Antonio Gonzalez da, Souza, C. A., Oliveira, A. C. d., Luche, H. d. S., Zimmer, C. M., Hawerroth, F. J., Schiavo, J., Sponchiado, J. C. 2015. Lodging reduction in white oat using the plant growth regulator trinexapac-ethyl. Pesquisa Agropecuária Brasileira 50: 115-125.

Health Canada. 2010. Oat Products and Blood Cholesterol Lowering. [Online] Available http://hc-sc.gc.ca/fn-an/label-etiquet/claims-reclam/assess-evalu/oat-avoine-eng.php [3 Jan 2017].https://static.agcanada.com/wpcontent/uploads/2017/02/YAB170227.pdf#_ga=2.89107229.762070094.1506275861-685548685.1506275861 [20 September. 2017].

Humphreys, D., Smith, D., Mather, D. 1994. Nitrogen fertilizer and seeding date induced changes in protein, oil and β-glucan contents of four oat cultivars. J. Cereal Sci. 20: 283-290.

Jackson, G., Berg, R., Kushnak, G., Blake, T., Yarrow, G. 1994. Nitrogen effects on yield, beta-glucan content, and other quality factors of oat and waxy hulless barley. Communications in Soil Science and Plant Analysis 25: 3047-3055.

Kaspary, TE, Lamego, FP, Bellé, C., Kulczynski, SM and Pittol, D., 2015. Growth regulator in productivity and quality of white oat seeds. Planta Daninha. 33:739-750.

Kelbert, A., Spaner, D., Briggs, K., King, J. 2004. Screening for lodging resistance in spring wheat breeding programs. Plant Breeding 123: 349-354.

Knaggs, P. J. 2002. Yield physiology, quality and soil water dynamics of a semi dwarf and a tall oat (Avena sativa L.) cultivar. M.Sc. Thesis, University of Manitoba, Winnipeg, MB.

Knapp, J. and Harms, C. 1988. Nitrogen fertilization and plant growth regulator effects on yield and quality of four wheat cultivars. J. Prod. Agric. 1: 94-98.

Ladizinsky, G., 2012. Studies in oat evolution: A man's life with Avena. Springer Science & Business Media.

Lafond, G., May, W., Holzapfel, C. 2013. Row spacing and nitrogen fertilizer effect on no-till oat production. Agron. J. 105: 1-10.

Laverick, R. M. 1997. Winter oats: Agronomy review. Winter Oats: Agronomy Review.

Lichtenthaler, H. K. 1999. The 1-deoxy-D-xylulose-5-phosphate pathway of isoprenoid biosynthesis in plants. Ann. Rev Plant Bio. 50: 47-65.

Luckwill, L. C. 1981. Growth regulators in crop production. Edward Arnold Ltd.

Mäkelä, P., Väärälä, L., Peltonen-Sainio, P. 1996. Agronomic comparison of Minnesota-adapted dwarf oat with semi-dwarf, intermediate, and tall oat lines adapted to northern growing conditions. Can. J. Plant Sci. 76: 727-734.

Maral, H., Dumlupinar, Z., Dokuyucu, T., Akkaya, A. 2013. Response of six oats (avena sativa) cultivars to nitrogen fertilization for agronomical traits. Turk J. Field Crops 18: 254-259.

Marolli, A., da Silva, J.A., Romitti, M.V., Mantai, R.D., Hawerroth, M.C. and Scremin, O.B., 2017. Biomass and grain yield of oats by growth regulator. Revista Brasileira de Engenharia Agrícola e Ambiental, 21:163-168.

Marshall, H., Kolb, F., Roth, G. 1987. Effects of nitrogen fertilizer rate, seeding rate, and row spacing on semidwarf and conventional height spring oat. Crop Sci. 27: 572-575.

Marshall, H., McDaniel, M., Cregger, L. 1992. Cultural practices for growing oat in the United States. Oat Sci. Tech. 191-221.

Matysiak, K. 2006. Influence of trinexapac-ethyl on growth and development of winter wheat. Journal of Plant Protection Research 46: 133-143.

May, W. E., Mohr, R. M., Lafond, G. P., Johnston, A. M., Craig Stevenson, F. 2004. Effect of nitrogen, seeding date and cultivar on oat quality and yield in the eastern Canadian prairies. Can. J. Plant Sci. 84: 1025-1036.

McCleary, B. V. and Codd, R. 1991. Measurement of (1→ 3), (1→ 4)-β-D-glucan in barley and oats: A streamlined enzymic procedure. J. Sci. Food Agric. 55: 303-312.

Mitchell Fetch, J. W., Tekauz, A., Brown, P. D., Ames, N., Chong, J., Fetch Jr, T. G., Haber, S. M., Menzies, J. G., Townley-Smith, T. F., Stadnyk, K. D. 2013. Stride oat. Can. J. Plant Sci. 93: 1-5.

Mohr, R., Grant, C., May, W., Stevenson, F. 2007. The influence of nitrogen, phosphorus and potash fertilizer application on oat yield and quality. Can. J. Soil Sci. 87: 459-468.

Mourtzinis, S., Conley, S. P., Gaska, J. M. 2015. Agronomic management and fungicide effects on oat yield and quality. Crop Sci. 55: 1290-1294.

Mulder, E. 1954. Effect of mineral nutrition on lodging of cereals. Plant and Soil. 5: 246-306. [Online] Available https://doi.org/10.1007/BF01395900 [19 March. 2016].

Murphy, J. P. and Hoffman, L. 1992. The origin, history, and production of oat. Oat Sci. and Tech. 1-28.

Muurinen, S., Kleemola, J., Peltonen-Sainio, P. 2007. Accumulation and translocation of nitrogen in spring cereal cultivars differing in nitrogen use efficiency. Agron. J. 99: 441-449.

Neenan, M. and Spencer-Smith, J. 1975. An analysis of the problem of lodging with particular reference to wheat and barley. J. Agric. Sci. 85: 495-507.

Nolte, K. 2007. The PGR trinexapac-ethyl reduces lodging in desert durum wheat. Hortscience, Amer. Soc. Horticultural Science 113 S West St, Ste 200, Alexandria, VA 22314-2851 USA.

Ohm, H. 1976. Response of 21 oat cultivars to nitrogen fertilization. Agron. J. 68: 773-775.

Peltonen, J. and Peltonen-Sainio, P. 1997. Breaking uniculm growth habit of spring cereals at high latitudes by crop management. II. tillering, grain yield and yield components. J. Agron. Crop. Sci. 178: 87-95.

Peltonen-Sainio, P. 1991. Productive oat ideotype for northern growing conditions. Euphytica 54: 27-32.

Peltonen-Sainio, P. and Peltonen, J. 1995. Floret set and abortion in oat and wheat under high and low nitrogen regimes. Eur. J. Agron. 4: 253-262.

Peltonen-Sainio, P. and Rajala, A. 2001. Chlormequat chloride and ethephon affect growth and yield formation of conventional, naked and dwarf oat. Agric. Food Sci. 165-174. [Online] Available at: <https://journal.fi/afs/article/view/5691>. [04 Aug. 2016].

Peltonen-Sainio, P. and Rajala, A. 2001. Chlormequat chloride and ethephon affect growth and yield formation of conventional, naked and dwarf oat. Agric. Food Sci. 165-174.

Peltonen-Sainio, P., Granqvist, M., Säynäjärvi, A. 1993. Yield formation in modern and old oat cultivars under high and low nitrogen regimes. J. Agron. Crop Sci. 171: 268-273.

Penckowski, L. H., Zagonel, J., Fernandes, E. C. 2009. Nitrogen and growth reducer in high yield wheat. Acta Scientiarum.Agronomy 31: 473-479.

Pendleton, J. 1954. The effect of lodging on spring oat yields and test weight. Agron. J. 46: 265-267.

Peterson, D. 1991. Genotype and environment effects on oat beta-glucan concentration. Crop Sci. 31: 1517-1520.

Pietola, L., Tanni, R., Elonen, P. 1999. Responses of yield and N use of spring sown crops to N fertilization, with special reference to the use of plant growth regulators Agric. Food Sci. 8: 423-440.

Pinthus, M. J. 1974. Lodging in wheat, barley, and oats: The phenomenon, its causes, and preventive measures. Adv. Agron. 25: 209-263.

Prentice, N., Babler, S., Faber, S. 1980. Enzymic analysis of beta-D-glucans in cereal grains. Cereal Chem. 57: 198-202.

Rademacher, W., Temple-smith, K. E., Griggs, D. L., Hedden, P. 1992. The mode of action of acylcyclohexanediones - a new type of growth retardant. Pages 571-577, In Progress in Plant Growth Regulation. Springer Netherlands.

Rademacher, W. 2000. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. Ann. Rev. Plant Bio. 51: 501-531.

Rajala, A. 2008. Plant growth regulators to manipulate oat stands. Agric. Food Sci. 186-197 [Online], Available at: <https://journal.fi/afs/article/view/5786. [11 Mar. 2015].

Rajala, A., and Peltonen-Sainio, P. (2000). Manipulating yield potential in cereals using plant growth regulators, Pages 27–70. In. A. Basra ed. Plant Growth Regulators in Agriculture and Horticulture: Their Role and Commercial Uses Food Products Press, New York.

Rajala, A. and Peltonen-Sainio, P. 2001. Plant growth regulator effects on spring cereal root and shoot growth. Agron. J. 93: 936-943.

Rajala, A. and Peltonen-Sainio, P. 2002. Timing applications of growth regulators to alter spring cereal development at high latitudes. Agric. Food Sci. 233-244. [Online], Available <https://journal.fi/afs/article/view/5721>.

Redaelli, R., Del Frate, V., Bellato, S., Terracciano, G., Cacciotti, R., Germeier, C. U., De Stefanis, E., Sgrulletta, D. 2013. Genetic and environmental variability in total and soluble β-glucan in European oat genotypes. J. Cereal Sci. 57: 193-199.

Rodionova, N.A., Soldatov VN, Mereshko B.E., Jarosh N.P and Kobylyanski, V.D. 1994. *Oat* Kolos, Moscow (Russian).

Ross, W. 1955. Associations of morphological characters and earliness in oats. Agron. J. 47: 453-457.

Saastamoinen, M., Hietaniemi, V., Pihlava, J. 2008. ß-Glucan contents of groats of different oat cultivars in official variety, in organic cultivation, and in nitrogen fertilization trials in Finland. Agric. Food Sci. 13: 68-79.

Salisbury, F.B., 1985. Plant adaptations to the light environment. In Plant production in the North: proceedings from Plant Adaptation Workshop, Tromso, Norway, September 4-9, 1983. Ase Kaurin, Olavi Juntilla and Jarle Nilsen. Tromso, eds. Norwegian University Press, 1985.

Sandhu, B. and Horton, M. 1977. Response of oats to water deficit. I. Physiological characteristics. Agron. J. 69: 357-360.

Saskatchewan seed guide. [Online] Available: http://www.saskseed.ca/images/varieties2016.pdf

Setter, T., Laureles, E., Mazaredo, A. 1997. Lodging reduces yield of rice by self-shading and reductions in canopy photosynthesis. Field Crops Res. 49: 95-106.

Shanahan, J., Smith, D., Welsh, J. 1984. An analysis of post-anthesis sink-limited winter wheat grain yields under various environments. Agron. J. 76(4): 611-615.

Simmons, S., Oelke, E., Wiersma, J., Lueschen, W., Warnes, D. 1988. Spring wheat and barley responses to ethephon. Agron. J. 80(5): 829-834.

Soils of Canada [Online] Available http://www.soilsofcanada.ca/orders/index.php [2016 Dec. 21].

Sorrells, M. and Simmons, S. R. 1992. Influence of environment on the development and adaptation of oat. Oat Sci. Tech. 115-163.

Stapper, M. and Fischer, R.A., 1990. Genotype, sowing date and plant spacing influence on high yielding irrigated wheat in southern New South Wales. II. Growth, yield and nitrogen use. Aus. J. Agric. Research., 41:1021-1041.

Statistics Canada. 2004. Census of Agriculture - Historical Data. [Online] Available: http://www.statcan.ca/english/Pgdb/agrc27a.html [29 Dec. 2014].

Statistics Canada (2014). Historical Data. [Online] Available http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/prim11b-eng.html [15 May. 2015].

Tamm, I. 2003. Genetic and environmental variation of grain yield of oat varieties. Agronomy Research 1: 93-97.

Tisdale, S.L., Werner, L.N., Beaton, J.D. and Hanlin, J. 1993. Soil fertility and fertilizers.

U.S. Department of Agriculture, National Agricultural Statistics Service, (2008). [Online] http://www.nass.usda.gov/Data_and_Statistics/index.asp Accessed [3 September, 2015].

U.S. Department of Agriculture, National Agricultural Statistics Service, (2017). [Online] Available http://usda.mannlib.cornell.edu/usda/current/worldag-production/worldag-production-07-12-2017.pdf. [ 3 Jun, 2017].

Van Sanford, D., Grove, J., Grabau, L., MacKown, C. 1989. Ethephon and nitrogen use in winter wheat. Agron. J. 81: 951-954.

Wang, X., Storsley, J., Thandapilly, S.J. and Ames, N., 2016. 43781. Effects of Processing, Cultivar, and Environment on the Physicochemical Properties of Oat β-Glucan. Cereal chemistry, 93: 402-408.

Welch, R. W., Leggett, J. M., Lloyd, J. D. 1991. Variation in the kernel (1→ 3)(1→ 4)-β-D-glucan content of oat cultivars and wild Avena species and its relationship to other characteristics. J. Cereal Sci. 13: 173-178.

White, E., McGarel, A., Ruddle, O. 2003. The influence of variety, year, disease control and plant growth regulator application on crop damage, yield and quality of winter oats (avena sativa). The Journal of Agricultural Science 14001: 31-42.

Wiersma, D.W., Oplinger, E.S. and Guy, S.O., 1986. Environment and cultivar effects on winter wheat response to ethephon plant growth regulator. Agron. J. 78:761-764.

Wiersma, J., Dai, J., Durgan, B. 2011. Optimum timing and rate of trinexapac-ethyl to reduce lodging in spring wheat. Agron. J. 103: 864-870.

Wiggans, S. and Frey, K. J. 1957. Tillering studies in oats II. effect of photoperiod and date of planting. Agron. J. 49(4): 215-217.

Winfield, K., Hall, M., Paynter, B. 2007. Milling oat and feed oat quality-what are the differences.

Wood, P. J. 1993. Physicochemical characteristics and physiological properties of oat (1→ 3),(1→ 4)-β-D-glucan. Oat Bran. St. Paul, MN, USA: Amer. Assoc.Cereal. Chem 70: 83-112.

Wood, P. J. 1994. Evaluation of oat bran as a soluble fibre source. characterization of oat β-glucan and its effects on glycaemic response. Carbohydr. Polym. 254: 331-336.

Wood, P.J., 2007. Cereal β-glucans in diet and health. J Cer Sci, 46(3) 230-238.

Yan, W., Fregeau-Reid, J., Martin, R., Pageau, D., Xue, A., Jakubinek, K., DeHaan, B., Thomas, S., Hayes, M. and Cummiskey, A., 2016. AAC Kolosse oat. Can. J. Plant Sci. 97:1-4.

Yang, R. 2010. Towards understanding and use of mixed-model analysis of agricultural experiments. Can. J. Plant Sci. 90: 605-627.

Zadoks, J.C., Chang, T.T. and Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed research, 14: 415-421.

Zagonel, J., Venancio, W., Kunz, R. 2002. Effect of growth regulator on wheat crop under different nitrogen rates and plant densities. Planta Daninha 20: 471-4.

Zhou, M., Roberts, G., Robards, K., Glennie-Holmes, M. 1998. The effects of sowing date, nitrogen application, and sowing rate on oat quality. Aust. J. Agric. Res. 49: 845-852.

Zhu, L., Shi, G.X., Li, Z.S., Kuang, T.Y., Li, B., Wei, Q.K., Bai, K.Z., Hu, Y.X. and Lin, J.X., 2004. Anatomical and chemical features of high-yield wheat cultivar with reference to its parents. Acta botanica sinica-english edition, 46(5), 565-572.

Zute, S. and Gruntiņa, M. 2002. Grain yield of oats and different factors influencing it under growing conditions of Latvia. Agriculture: Research Works of Biometrical Sciences, Agronomy, Lithuanian Institute of Agriculture, Lithuania, Akademija: 71-77.

Zwer P.K. 2016 Oats: Overview Encyclopedia of Food Grains. Elsevier Sci. Tech, 2016.