NITROGEN AND PHOSPHORUS RECALIBRATION FOR SUNFLOWER IN NORTH DAKOTA

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Nitrogen and Phosphorus Recalibration for Sunflower in North Dakota

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ABSTRACT

Sunflower is one of the most important annual crops grown for edible oil in the world and is grown in North Dakota and the northern Great Plains more than any other region in the United States. Sunflower production and sunflower itself has evolved significantly since commercial cultivation began in the 1970s. In order to properly update fertility requirements of nitrogen and phosphorus in the northern Great Plains to correspond to this evolution, sunflower yield and oil concentration response to nitrogen and phosphorus fertilizer was investigated based on a two-year (2014-2015) study. Highly significant statistical relationships between sunflower yield and oil concentration were found with nitrogen fertilizer rate but were not found with phosphorus fertilizer rate. This indicates that nitrogen fertilizer application rates used for sunflower need to be determined by current documented responses and that phosphorus fertilizer may not be needed to produce optimal yield and oil concentration of sunflower.

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DEDICATION

To my grandfathers, the late Robert Schultz, the late Louis Woehler, and Charles Carlson, who instilled within my family and myself a passion for agriculture and the importance of education.

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GENERAL INTRODUCTION

Sunflower is a relatively new crop to the United States (U.S.) with commercial cultivation beginning in the 1970s, and ever since this time sunflower has been an important crop in agricultural production systems in the northern Great Plains regional states of North Dakota, South Dakota, and Minnesota. Throughout its production history sunflower has evolved with innovations and transitions in cultural and environmental factors of production and genetic-based solutions that have collectively improved yield potentials (Figure 1) (USDA-NASS, 2015; Hulke and Kleingartner, 2014). Approximately 85% of U.S. sunflower production is in the northern Great Plains (USDA-NASS, 2015) and sunflower is considered one of the most important annual crops grown for edible oil in the world (Putt, 1997).

Sunflower fertility requirements of nitrogen (N) and phosphorus (P) in the northern Great Plains were determined through establishment of soil test calibration and associated critical N and P levels, and yield and oil concentration responses by investigations of sunflower when it first became a commercially cultivated crop. North Dakota State University soil scientist Joseph Zubriski and University of Minnesota agronomy professor Robert Robinson headed the original study of sunflower N and P requirements in the northern Great Plains in the 1970s and 1980s (Robinson, 1985; Zubriski and Moraghan, 1983; Zubriski et al., 1979; Cheng and Zubriski, 1978; Faulkner, 1977; Zubriski and Zimmerman, 1974; Robinson 1973a; Robinson 1973b). These investigations occurred in the time period between one of the first published sunflower guides which included a fertility aspect (Wilkins and Swallers, 1972) and current published sunflower fertility recommendations (Kaiser et al., 2011; Franzen, 2010, Gerwing and Gelderman, 2005), which have not significantly changed since 1981 (Dahnke, 1981).

Soil test calibration for sunflower was a major research activity when commercial cultivation and soil testing programs began and it is recognized that soil test calibrations should be continually updated (Heckman et al., 2006; Peck and Soltanpour, 1990). In this thesis, N and P are calibrated on the basis of sunflower yield and oil concentration responses in North Dakota. The calibration and responses are for modern sunflower cultivars, are applicable for current sunflower production systems, and establish critical levels of N and P throughout the northern Great Plains region of sunflower production. The overall objective of this research is to develop modern N and P recommendations for sunflower in the northern Great Plains from the collected calibration dataset of documented responses to N and P fertilizer of sunflower yield and oil concentration. Other objectives include utilizing the dataset to compare relationships between N and P fertilizer and other aspects of sunflower production, such as sunflower plant lodging potential and economic feasibility of fertilizer application upon results of individual site-year and regional site-year analysis.

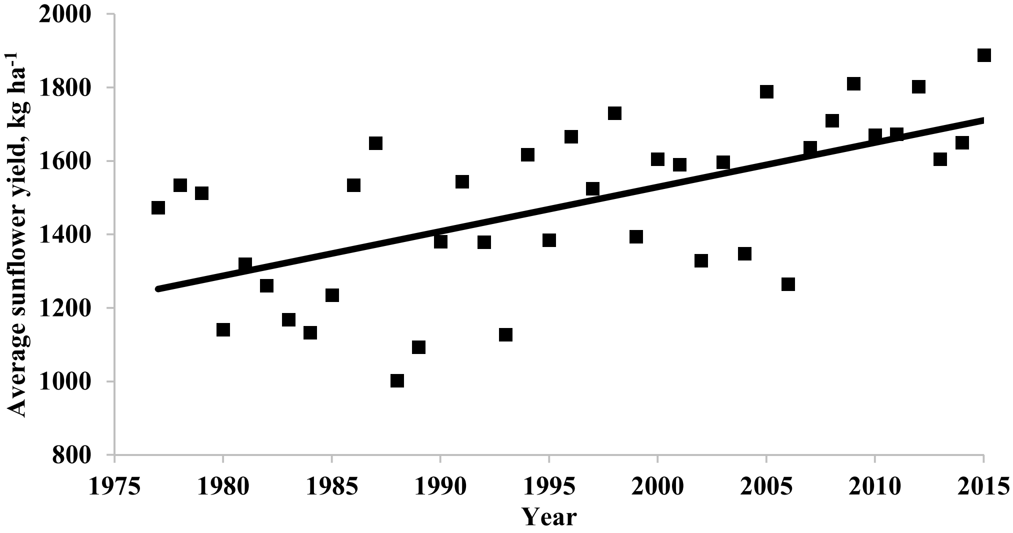

Figure 1. Relationship between average sunflower yield for the northern Great Plains states of North Dakota, South Dakota, and Minnesota and year, from 1977 to 2015.

The remainder of this thesis is organized as follows: chapter “LITERATURE REVIEW” provides a thorough review of sunflower N and P requirements and relevant documented work on sunflower fertility responses, with focuses on sunflower yield and oil concentration; chapter “INTRODUCTION” in which the literature is summarized pertaining to the objectives of the study; chapter “MATERIALS AND METHODS” includes the experimental data for the two-year study including site-years, soil test results, fertilization and plot design, sunflower cultivar information, and sunflower yield and oil concentration data collection and statistical analysis methods; chapter “RESULTS AND DISCUSSION FOR OILSEED SUNFLOWER”, chapter “RESULTS AND DISCUSSION FOR CONFECTIONARY SUNFLOWER”, and chapter “RESULTS AND DISCUSSION FOR SITE-YEARS CATEGORIZATION” where the datasets from individual site-years and categorized site-years statistical relationships between sunflower yield, oil concentration, and lodging are presented and discussed; and last, chapter “GENERAL CONCLUSIONS” in which the entire study is synthesized.

LITERATURE REVIEW

Sunflower

Sunflower Origin and Crop

Sunflower (*Helianthus annuus* L.) is a native plant of North America. The American Indians first cultivated sunflower 5,000 years ago in the present-day southwest United States (Semelczi-Kovacks, 1975). Sunflower spread to the north and east in North America, where it was domesticated 4,000 years ago (Blackman et al., 2011). Numerous American Indian tribes grew sunflowers in their culture, including the Hopi, Mandan, Arikara, Hidatsa, and Algonquin (Heiser, 1955; Putt, 1997). Eventually sunflower expanded from the North American tribes to Europe with Spanish explorers in the early 1500s. The American Indians used sunflower primarily as a food source, however, the geographic range of sunflower widened in Europe to Italy and France first as an ornamental plant. By the late 1500s, sunflower was also grown in gardens in Belgium, the Netherlands, Switzerland, Germany, and England (Putt, 1997). In 1568, the Flemish herbalist Rembertus Dodonaeus is credited with the first published description of sunflower (Heiser, 1951; Gundaev, 1971). Italian botanists Giacomo Antonio Cortuso and Pietro Andrea Mathhiolus published detailed descriptions as well, and are credited with the dissemination of sunflower (Semelczi-Kovacks, 1975).

After the initial expansion in Europe as a garden plant, sunflower was recognized in 1716 for its source as an industrial oil in an English patent (Putt, 1997). Cultivation for oil began shortly thereafter, however, it was not until expansion into Russia in the 18th century that sunflower oil became popular as a food (Heiser, 1955). Likewise, the practice of eating whole sunflower seed is not noted as becoming common until 1740. Russia and far-eastern European countries developed sunflower commercially, with Russia growing 150,000 ha in 1880 (Putt, 1997). Sunflower, cultivated mainly for the manufacture of oil in Russia and far-eastern Europe, became competitive with rapeseed (*Brassica napus* L.).

Following sunflower's development in Europe, it was then introduced back into North America during the 19th century and American farmers ordered sunflower seed from Russia shortly thereafter (Putt, 1997). Russian peasants developed the first cultivars in Russia and one particular cultivar, 'Mammoth Russian', was popular as a tall, late-maturing cultivar ordered by American farmers and grown in the U.S. (Heiser, 1976). First cultivation of sunflower in the U.S. was primarily for silage and as a poultry scratch feed, but there was also some interest in crushing seed for oil production (Putt, 1997; Heiser, 1976). Even though further investigations on growing sunflower were conducted from West Virginia to Washington, the evolution of sunflower as a significant agricultural crop was prevented due to doubts about oil value, competition from other oilseed crops, and imported oil supplies (Putt, 1997).

The transition to growing sunflower as an oilseed in Russia expanded sunflower's potential in North America, beginning in Canada. The first breeding nursery was developed in Saskatchewan in 1937 and a cross between a Mennonite cultivar and the Russian S-490 (Russian oil cultivar) created one of the first available cultivars for growers in North America (Putt, 1997). Production significantly increased as breeding efforts improved disease resistance and increased oil content and new cultivars were available. Beginning in 1948, farmers in the southern Red River Valley in Minnesota and North Dakota became interested in growing sunflowers after production shifted from Alberta and Saskatchewan to Manitoba and profitable economic returns were realized. The early hybrid 'Advent' from Canada and the cultivar Peredovik from Russia were high-yielding varieties that made the crop attractive to U.S. farmers. The U.S. oilseed-processing industry recognized that high oil concentration of sunflower was economically profitable and commercial crushing began in 1967 (Putt, 1997). Prior to oilseed sunflower becoming economically important, sunflower hectares in the U.S. were primarily devoted to non-oilseed varieties (Berglund, 2007).

Sunflower Types

Two types of sunflower are grown in the U.S.; oilseed and non-oilseed. Oilseed sunflower dominates the U.S. sunflower market, occupying approximately 80 percent of all sunflower acreage (USDA-NASS, 2014a). Oilseed sunflowers tend to be small seeded and black, and are widely used for vegetable oil production and birdseed (Berglund, 2007). Seed of the oilseed varieties contains from 38 to 50 percent oil. Non-oilseed sunflower, also known as confectionary sunflower, are large seeded and striped. Confectionaries are grown on the remaining 20 percent of sunflower acreage and are used for human consumption as nuts or in-shell seeds (Berglund, 2007).

Global and U.S. Sunflower Production

Major sunflower-producing countries or regions are the former Soviet Union, Argentina, Eastern Europe, U.S., China, France, and Spain (Sandbakken and Kleingartner, 2007). These countries and regions produce nearly all of the world’s sunflowers. The former Soviet Union and Argentina continue to be the world’s largest producers of sunflower, while the U.S. has ranked sixth in annual production in recent years (National Sunflower Association, 2015).

In 1962, total U.S. sunflower planted area is estimated to have been 16,200 ha and increased to 89,840 ha in 1970 (Thomason, 1974). During the 1970s, sunflower expanded substantially and the U.S. Department of Agriculture (USDA) began providing production reports that included sunflower. The geographic nature of sunflower production, and its subsequent spread, is reflected in these production reports. Minnesota, North Dakota, South

Dakota, and Texas were included in the first production reports, followed by Kansas, Colorado, and Nebraska beginning in the 1990s, while California and Oklahoma were added in the late 2000s. Today, the High Plains (Kansas, Nebraska, and Oklahoma) and northern Great Plains (Minnesota, South Dakota, and North Dakota) regions produce nearly all U.S. sunflowers.

The peak of U.S. sunflower production occurred in 1979 with over 2.3 million ha while producing about 15 percent of the world's sunflowers (Sandbakken and Kleingartner, 2007). Following rapid sunflower production in the 1970s, production declined by more than two-thirds in the 1980s due to expanded foreign production and increased production of alternate oil crops (primarily soybeans (*Glycine max* L. Merr.)) by U.S. farmers (Ash, 2015). The U.S. share of world production has continued to decline in recent years as foreign sunflower-producing countries (Argentina, Russia, and Ukraine) have increased production. In 2005, the U.S. market share of global production was only 6 percent (Sandbakken and Kleingartner, 2007) with just over 1 million ha (USDA-NASS, 2014b).

Northern Great Plains Sunflower Production

The northern Great Plains region presently produces about 85 percent of all U.S. sunflowers (USDA-NASS, 2015). Of which, North Dakota and South Dakota combine to produce nearly 80 percent while Minnesota represents a significantly smaller portion, at around 5 percent. North Dakota has long been the nation's largest producer of sunflowers, however, South Dakota recently surpassed North Dakota in total production. Total production in South Dakota in 2014 and 2015 was 398 and 558 million kg, respectively, while North Dakota total production was 385 and 485 million kg, respectively (USDA-NASS, 2015; USDA-NASS, 2016).

Sunflower Production Evolution

Average sunflower yields in the northern Great Plains have increased substantially since commercialization, growth, and hybrid variety breeding in sunflower began in the early 1970s (Figure 1) (Hulke and Kleingartner, 2014) which this can be attributed to several factors that have evolved over the past 40 years. Defensive breeding has presented genetics-based solutions provided in resistance to downy mildew [*Plasmopara halstedii* (Farl.) Berl. & de Toni], sunflower rust (*Puccinia helianthi* Schw.), and Sclerotinia [*Sclerotinia sclerotiorum* (Lib.) de Bary], as well as herbicide resistance systems. Seed treatments are commercially available for protection against disease pathogens, insects, and seed-eating herbivores contributing to more even plant stands. Other coated planting seed has also become available to aid with seed placement and planting. Unfortunately, planters are designed for corn (*Zea mays* L.), soybean, and small grain production and sunflower seed is not always uniform in size and weight, resulting in problems while planting and reduced plant stands due to planter skips (Hulke and Kleingartner, 2014; Lilleboe, 2012; Smith and Kocher, 2008).

The sunflower cultivars that are currently planted are very different than cultivars from 40 years ago (Hulke and Kleingartner, 2014). Differences in the genetics of current varieties may have different nutrient responses than those used in past sunflower and soil test calibration studies (Conyers, 1999). What may be a low concentration of a nutrient for one variety or cultivar may not necessarily be low for another. It is expected that the calibration of a soil test may vary with different cultivars of a plant due to root geometry, rhizosphere chemistry alterations, and accessibility to water in the soil profile which suggests that a certain critical level of a nutrient may only be related to a certain genotype or mixture of genotypes (Conyers, 1999). For sunflower, breeding objectives vary with specific breeding programs (i.e., achene and kernel characteristics, disease and insect resistance, and drought tolerance) but generally emphasize high seed yield and high oil content (Fick and Miller, 1997). The programs and two focal objectives are inherently tied, as improvements in disease, insect, and pest resistance directly impact achievements in seed yield and oil content. Generally, from an agronomic perspective, characteristics that are associated with good vegetative plant growth are correlated with high yield (Fick and Miller, 1997). These characteristics include days from sowing to maturity, plant height, head diameter, stem diameter, leaf area per plant, seed number per plant, and seed weight (Fick, 1978; Skoric, 1988). Altering the genetic make-up of sunflower in these respects influences sunflower uptake of nutrients and nutritional requirements.

Sources of improved levels of tolerance for most diseases are available among cultivated sunflower and especially the wild species of *Helianthus* (Skoric, 1988; Seiler, 1992). Sunflower rust, downy mildew, Sclerotinia stalk and head rot, Verticilium wilt (*Verticillium dahlia* Kleb.), and phomopsis (*Diaporthe helianthi* Munt.-Cvet. et al.) are common diseases that are detrimental to sunflower, producing yield losses between 1 to 80% (Fick and Zimmer, 1975; Zimmer and Hoes, 1978; Purdy, 1979; Gulya et al., 1989). Wild sunflower genotypes and inbred lines in resistance breeding offer the most effective means of controlling these diseases and are incorporated into almost all sunflower grown today (Fick and Miller, 1997).

Prior to 2000, only dinitroaniline (DNAn) herbicides were available for weed control in sunflower production (Hulke and Kleingartner, 2014), which only suppressed most broadleaf weeds (Blamey et al., 1997; Lilleboe, 1997) and required timely rainfall and shallow tillage for activation (Blamey et al., 1997). Starting in 2000, the development and incorporation of herbicide resistance genes into sunflower allowed additional herbicides to become available for sunflower (Hulke and Kleingartner, 2014; Miller and Al-Khatib, 2002, 2004). The preplant herbicides and post-emergent herbicide products provided increased management of formerly difficult-to-control small seeded broadleaf and grass weeds and allowed farmers to utilize reduced tillage systems (Hulke and Kleingartner, 2014; Ashley and Tanaka, 2007). This increased the cultivation of sunflower in more arid regions of western North Dakota and South Dakota, western Kansas, eastern Colorado, and the Texas panhandle where no-till practices are commonly utilized. These more arid regions are limited in precipitation, however, disease occurrence can be reduced compared to the previously most common regions of sunflower production (eastern North Dakota and South Dakota, eastern and central Kansas).

Sunflower Fertility

General Sunflower Fertility Requirements

Sunflower requires 16 chemical elements for growth (Blamey et al., 1997) that are defined as essential because (i) a deficiency of the element makes it impossible for the plant to complete its life cycle, (ii) a deficiency of the element can only be alleviated by supplying the element, and (iii) the element is directly involved in the nutrition of the plant (Arnon and Stout, 1939). Sunflower essential elements include non-mineral elements C, H, and O, and mineral elements N, P, K, Ca, Mg, S, Zn, B, Mn, Mo, Fe, Cu, and Cl. Sunflower total uptake of essential elements (in nutrient form) from the soil in g or mg per kg of sunflower dry matter (all plant parts) is presented in Table 1 and nutrient mass accumulation in sunflower seed in g or mg per kg of sunflower seed (removed with yield) is presented in Table 2.

Nitrogen in Sunflower Production

Nitrogen function and plant composition

In sunflower, N is an active component in the production of amino acids that are subsequently combined into proteins and nucleic acids and N has a major association with photosynthesis as an integral part of photosynthetic enzymes, such as ribulose-1,5-bisphosphate carboxylase/oxygenase (rubisco), and chlorophyll (Havlin et al., 2005; Mengel et al., 2001; Connor and Hall, 1997). Generally, 75% of the leaf N content of sunflower is associated with photosynthesis (Evans, 1989) and rubisco accounts for 50% of sunflower soluble leaf protein (Gimenez et al., 1992). Once absorbed, most N is translocated directly to sunflower leaves where, in association with photosynthesis, it is reduced to amino acids, some of which are translocated to sites of active growth (Merrien et al., 1988; Hocking and Steer, 1983b; Kaiser and Lewis, 1980). Mobilization of N within sunflower, particularly from rubisco as leaves senesce, results in translocation to expanding leaves and, as sunflower matures, approximately 60% of total N to the seed (Connor and Hall, 1997; Gachon, 1972). Apparent redistribution of N between anthesis and physiological maturity was averaged for seven sunflower hybrids with four N treatment rates by Steer et al., (1985), and they found that with increasing N supply (0, 30, 90, and 150 kg N ha^{-1}) the redistribution of N from stems, petioles, and leaves decreases from 69.3, 73.7, and 70.6 to 51.3, 54.0 and 62.8%, respectively. These authors concluded that the magnitude of N redistribution may be influenced by the demand for N by the seeds, metabolic functions in the leaves, and uptake of N by roots during seed-filling. Sunflower stores proportionally more N in stems than in seeds with higher available N for uptake after anthesis is reached (Steer and Hocking, 1984), resulting in decreased redistribution percentage of N and seed N percent. The distribution of total N in sunflower plant parts at physiological maturity has been found to be 10.5% in stem, 13% in leaves, 11% in head, and 65.5% in seed by Heard et al., (2006) and Vrebalov et al., (1980). Hocking and Steer (1982) found that sunflower seeds accumulate 68% of the total plant N, with 43% redistributed from vegetative parts, and 36% of redistributed N is contributed by leaves and 7.5% from the stem (Vrebalov, 1974). However, limited N availability during seed filling may restrict the other 50% of N needed for seed accumulation from the soil, and, as Vrebalov (1974) showed, over 75% of N can be redistributed from vegetative plant parts in such case.

Table 1. Sunflower nutrient uptake from the soil in g or mg per kg of sunflower dry matter (all plant parts).

Nutrient	Robinson, (1973b)	Canadian Fertilizer Institute, (2001)	Heard et al., (2006)	Manitoba Agriculture, (2006)	Vigil et al., (2009)	Average
$g\ kg^{-1}$						
N	41.3	34.0 – 41.0	37.0 – 61.0	37.2	48.0	42.6
P_2O_5	5.1	12.0 – 14.0	12.0	12.8	15.0	11.6
K_2O	28.6	7.0 – 22.0		18.5	36.0	24.4
S	4.7	4.0 – 5.0	3.9 – 5.8	4.3	6.0	4.9
Ca	17.6		27.0 – 47.0		19.7	24.8
Mg	11.0		18.6 – 19.3		7.0	12.3
$mg\ kg^{-1}$						
Zn	99.0		40.0 – 60.0		90.0	80.0
B	65.0		150.0			106.0
Mn	55.0		90.0 – 150.0			87.5
Mo	29.0					29.0
Fe	261.0		270.0			266.0
Cu	19.0		10.0 – 40.0			22.0

Table 2. Nutrient mass accumulation in sunflower seed in g or mg per kg of sunflower seed (removed with yield).

Nutrient	Robinson, (1973b)	Seiler, (1986)	Hocking et al., (1987)	Merrien et al., (1986)	Heard et al., (2006)	Manitoba Agriculture, (2006)	Vigil et al., (2009)	Average
g kg^{-1}								
N	25.8	30.0		20.9	24.0 – 33.0	26.8	33.6	27.7
P_2O_5	3.9	6.9	4.3	7.0	9.0 – 13.0	8.0	13.4	7.7
K_2O	5.9	8.2	7.6	17.1		6.0	9.0	10.4
S	1.7		4.7		1.7 – 2.2		2.2	2.6
Ca	1.1	3.5	1.2	1.4	1.5 – 2.3		1.3	10.4
Mg	2.3	1.8	3.0	2.6	3.0 – 3.6		2.2	2.5
mg kg^{-1}								
Zn	48.0			44.0	20.0 – 40.0		56.0	44.5
B	14.0			25.0	20.0			19.7
Mn	14.0			13.0	20.0			15.7
Mo	6.0							6.0
Fe	33.0			34.0	30.0 – 40.0			34.0
Cu	13.0			8.0				10.5

Yield components of sunflower include seed number and size together (confectionary and oilseed sunflower) with oil concentration and type (oilseed sunflower), and are determined sequentially as- seed number, then size, and lastly oil content (Connor and Hall, 1997). Increasing N supply can increase seed number per head, seed mass, oil yield, leaf area, and leaf N content (Abbadi, 2008; Connor and Sadras, 1992; Hocking and Steer, 1989; Steer and Hocking, 1984). Restricted N supply can limit the size of floret generative area, and hence the number of florets established per head, each by 33% (Steer et al., 1985; Palmer and Steer, 1985), and can further limit the growth of the head (Sinsawat and Steer, 1993) leading to smaller individual florets. Seed number is established by the plant during floret initiation, usually a higher number of florets than what number will actually set seed, and the seeds are then subjected to a series of adjustments up to the start of seed growth, one being decreased size with limited N prior to anthesis (Connor and Hall, 1997; Steer et al., 1984). As opposed to seed number and seed size, high levels of available N can reduce seed oil concentration of oilseed sunflower. This occurs particularly after floral initiation or during seed filling when seed-protein content increases occur with available N and are accompanied by reductions in seed oil concentration (Blanchet et al., 1983; Blanchet and Merrien, 1982). The oil concentration of sunflower seed is significantly reduced at higher N supplies resulting from the dilution of oil in heavier seeds produced under high N nutrition, which is further supported by the increase of seed N (protein) concentration (Abbadi, 2008; Haby et al., 1982; Sharma and Verma, 1982; Blamey and Chapman, 1980). Absolute amounts of oil per seed may increase (Connor and Sadras, 1992; Steer et al., 1984), which is why typically even with decreased oil concentrations, greater N availability and supply to sunflower will increase oil yields.

Deficiency of N causes sunflower to grow slowly, decreases leaf area index, lowers radiation use efficiency, and lowers photosynthesis activity, as also occurs in other plants (Fageria and Baligar, 2005; Sinclair and Horie, 1989; Muchow, 1988). Nitrogen deficiency can also reduce sunflower plant height, stem diameter, rate of floret initiation, total number of florets, seed number and seed weight per plant, protein per seed and per plant, and oil yield per plant (Hocking and Steer, 1982). Nitrogen stress during the early vegetative period restricts leaf expansive, and may also reduce the number of leaves (Gimenez et al., 1994; Connor et al., 1993; Hocking and Steer, 1989; Steer and Hocking, 1983). If N supply to sunflower is inadequate, reduced growth and yield are expected (Fageria, 2009; Lopez-Bellido et al., 2003; Fageria and Baligar, 2001).

Sunflower uptake of N is dependent upon soil water content, the availablility within the soil, and root exploration (Connor and Hall, 1997). The timing of N fertilizer application is important in that early N deficiency (i.e., before floret initiation) may severely limit seed number (Blamey et al., 1997; Steer et al., 1984), while approximately 75% of total N uptake by sunflower is after the V8 (8 leaves) vegetative growth stage (Heard et al., 2006). Cheng and Zubriski (1978) found that sunflower uptake of N is complete by anthesis, but Loubser and Human (1993) and Hocking and Steer (1983b) found sunflower is still able to absorb between 25 to 35% of N requirements from the soil after anthesis.

Nitrogen requirements and responses

Nitrogen trials were conducted in North Dakota annually from 1971-1983 on dryland sunflower and from 1977-1983 for irrigated sunflower (Zubriski and Moraghan, 1983). In these experiments, sunflower yield increased and oil concentration decreased with increasing total known available N. Zubriski and Moraghan (1983) reported yields of 1,725 and 2,352 kg ha^{-1}

with 28 kg N ha^{-1} for dryland and irrigated sunflower, respectively, and 2,632 and 3,629 kg ha^{-1} yields with 168 kg N ha^{-1} for dryland and irrigated sunflower, respectively. Oil concentrations also decreased from 46.3 to 44.2% and 50.7 to 49.0% for dryland and irrigated sunflower (Zubriski and Moraghan, 1983). Zubriski and Zimmerman (1974) found that a yield of 2,800 kg ha^{-1} required a total of about 95 kg ha^{-1} of N and a yield of 3,000 kg ha^{-1} required a total of about 150 kg ha^{-1} of N. Yield was the primary focus in early experiments in North Dakota, but in 1974 oil concentration was included and provided crop quality response to N. Zubriski and Zimmerman (1974) measured significantly ($P < 0.05$) different oil concentrations of 48.1, 46.3, and 45.3% for N fertilizer treatments of 0, 56, and 112 kg ha^{-1}, respectively. Overall, Zubriski and Zimmerman (1974) concluded that oil concentration is reduced with the addition of higher rates of N fertilizer. Of 16 responding sites out of 23 total sites between 1971-1979, Zubriski et al., (1979) observed yields of 2,560, 2,766, and 2,800 kg ha^{-1} of seed requiring 45, 90, and 135 kg ha^{-1} of fertilizer N, respectively, for dryland production. Zubriski et al., (1979) also observed decreasing average oil concentrations with increasing N fertilizer treatments. Cheng and Zubriski (1978) reported significantly ($P < 0.05$) increased seed yields with N fertilizer at rates of 28, 56, and 112 kg ha^{-1} for irrigated sunflower while oil concentration was significantly ($P < 0.05$) reduced with the higher N rates. A seed yield of 2,900 kg ha^{-1} required 135 kg ha^{-1} of N for oilseed sunflower and 147 kg ha^{-1} of N for confectionary sunflower in Faulkner, (1977), and Faulkner concluded that oilseed and confectionary sunflower utilized 5 kg ha^{-1} of N to produce 100 kg ha^{-1} of seed. Zubriski and Moraghan (1983) summarized the yield and oil concentration data and N requirement of sunflower for earlier studies done in North Dakota for 32 trials on dryland and four trials under irrigation, shown in Table 4. Schatz et al., (1999) observed nonsignificant ($P < 0.05$) differences of sunflower yield between N treatments of 34, 67, and 101 kg N ha^{-1} over a 10 year study in North Dakota.

In Minnesota, Robinson (1973a) measured an insignificant ($P < 0.05$) difference between sunflower yields obtained with 0, 75, and 150 kg ha^{-1} of N fertilizer, but a significant difference in yield of 977 kg ha^{-1} with 224 kg ha^{-1} N treatment versus 567 kg ha^{-1} yield for 0 kg ha^{-1} N treatment. Robinson (1973b) concluded that a sunflower crop requires about 220 kg ha^{-1} of N to produce a crop yield of 2,250 kg ha^{-1}. Nitrogen treatments of 112 and 336 kg ha^{-1} resulted in no statistical yield differences ($P < 0.05$) in studies done during 1977-1978 (Robinson, 1985). Oil concentration of sunflower (Robinson, 1985) decreased significantly ($P < 0.05$) with the 336 kg ha^{-1} N treatment on dryland. Irrigated sunflower also did not statistically ($P < 0.05$) increase in yield with increasing N rates. Oil concentration for the irrigation treatments, however, did not decrease with the higher N treatment.

Sunflower response to N rate has also been extensively studied outside of North Dakota and Minnesota. A summary of selected studies from sunflower-producing regions is presented in Table 5. These studies represent a wide range of sunflower growing conditions in very different climates and soil types and as a result, response of sunflower to N rate is region-specific on a global scale. For example, Mollashahi et al., (2013) and Salih, (2013) observed increasing oil concentration with N rate, whereas in the Minnesota and North Dakota studies, oil concentration decreased with N rate. Similar general trends of sunflower response to N rate as in the Minnesota and North Dakota studies are also presented by Oyinlola et al., (2010), Zubillaga et al., (2002), Scheiner et al., (2002), Ozer et al., (2004), Nasim et al., (2012) and Mathers and Stewart, (1982); Darby et al., (2013); either increasing sunflower yield with N rate and/or decreasing sunflower oil concentration with N rate. In another response study of sunflower to N rate (rate not shown), sunflower distribution of N in stem was 20 kg ha^{-1}, in the leaf, 23 kg ha^{-1}, in the head, 17 kg ha^{-1}, and in the seed, 115 kg ha^{-1}, totaling a N requirement of 175 kg ha^{-1} of N for a 4,300 kg ha^{-1} seed yield (Vrebalov et al., 1980).

Many other experiments have also investigated N influence on sunflower (Malligawad et al., 2004: Ruffo et al., 2003; Legha and Giri, 1999; Tomar et al., 1999; Geleta et al., 1997; Sarkar et al., 1995; Loubser and Human, 1993; Khokani et al., 1993; Steer et al., 1986; Steer et al., 1984; Kandil, 1984; Hussein et al., 1980) finding mixed results, primarily increasing yield and decreasing oil concentration with increasing N rate, but some do not see any response at all (i.e. Tomar et al., 1999; Geleta et al., 1997). Vigil et al., (2001) published results of a High Plains region (Colorado, U.S.) sunflower N response study (Table 3) and concluded that sunflowers need about 56 kg N ha^{-1} per 1,120 kg ha^{-1} of potential sunflower yield. This recommendation was updated when the results of a 7-year study in the High Plains indicated that a 1,120 kg ha^{-1} sunflower yield requires between 67 and 78 kg N ha^{-1} (Vigil, 2009).

Table 3. Summary of selected yield and oil concentration sunflower response to N rate studies.

N rate	Yield	Oil concentration	Location/Water	Reference/Study
kg ha^{-1}	kg ha^{-1}	%		
0	833c[†]	50.6b	Nigeria, dryland	Oyinlola et al., (2010)
30	911bc	54.0a		
60	1089ab	56.0a		
90	1222a	57.5a		
120	1056ab	56.4a		
150	1000bc	54.8a		
0		53.7a	Argentina, dryland	Zubillaga et al., (2002)
46		50.4b		
92		48.8b		
138		49.3bc		
0		46.5a / 48.4a[‡]	Argentina, dryland	Scheiner et al., (2002)
150		44.3b / 47.6b		
300		43.8b / 47.4b		
0	2077d	41.8a	Turkey, irrigated	Ozer et al., (2004)
40	2309c	41.4a		
80	2524b	41.3ab		
120	2651a	39.8bc		
160	2704a	39.5c		
0	2290e	46.2a	Pakistan, dryland	Nasim et al., (2012)
60	2936d	46.1a		
120	3137c	43.8b		
180	3800a	41.0c		
240	3775b	40.6d		
0	1519d	39.7d	Iran, dryland	Mollashahi et al., (2013)
75	1639c	40.6c		
150	1724b	41.2b		
225	1825a	41.9		
0	1520a	24.21a	Sudan, dryland	Salih, (2013)
20	2410b	26.89ab		
40	3010c	27.87b		
80	3170c	29.66c		
0	1950a	48.5b / 45.5b	Texas, U.S., irrigated	Mathers and Stewart, (1982)
84	2850b	43.8a / 41.9a		
168	2760b	42.9a / 41.2a		
0		48.4a / 45.5b	South Africa, dryland	Blamey and Chapman, (1981)
60		47.4ab / 47.3a		
120		46.7b / 47.1a		
180		44.6c / 47.2a		
0	1538	39.2	Colorado, U.S., dryland	Vigil et al., (2001)
34	2072	38.0		
67	2090	37.4		
101	2224	36.9		
0	5533c	45.1b	Vermont, U.S., dryland	Darby et al., (2013)
67	4869b	42.9a		
101	4164a	43.1a		
134	4539ab	41.7a		

[†] Means with the same letter within the same column and study are not significantly different at $P < 0.05$.

[‡] Results from studies with more than one dataset of oil concentrations are separated by /.

Phosphorus in Sunflower Production

Phosphorus function and plant composition

Phosphorus is required in smaller amounts in sunflower than N, but plays the central role in energy transfers for chemical synthesis in adenosine triphosphate (ATP) (Connor and Hall, 1997). Phosphorus is an essential component in all metabolically active cells, in cell membranes, and nucleotides (within DNA and RNA), as well as in adenosine diphosphate (ADP) and nicotinamide adenine dinucleotide phosphate (NADP) (Fageria, 2009; Grant et al., 2001; Mengel et al., 2001; Connor and Hall, 1997). Phosphorus, like N, is extensively mobilized, as roots, stem and petioles, leaves, head, florets, and seeds contain about 18, 18, 34, 11, 8, and 11% of P distribution at the beginning of anthesis and by maturity these same plant parts contain 3, 2, 8, 6, 2, and 79% of P (Hocking and Steer, 1983a). At physiological maturity, Vrebalov (1974) measured uptake of sunflower roots, stalks, leaves, head, and seed to total 1.28, 4.26, 2.92, 2.33, and 21.22 kg P_2O_5 ha^{-1}, respectively, or 4.0, 13.3, 9.1, 7.3, and 66.3% of total P, respectively. These studies (Hocking and Steer, 1983a; Vrebalov, 1974) concluded that total mobilization of P from sunflower stems and leaves to seeds can range from 30 to over 60%, and total P of seed can be up to 80%; while other experiments have found that 75% of sunflower total P accumulated in the seed (Sfredo et al., 1983; Gachon, 1972). Sunflower uptake from the soil and mass accumulation in seed of P is relatively low, 13.5 g kg^{-1} (Table 1) and 7.3 g kg^{-1} (Table 2), in comparison to N, even though accumulation is greatest in seed compared to other plant parts. Phosphorus in the seed accumulates primarily in lipoproteins, as phospholipids, and phytate (Connor and Hall, 1997). The concentration of P in sunflower seed (kernel plus hull) is 0.53%, of which, the kernel is between 0.65 and 0.69% P while the hull has a P concentration between 0.04

and 0.08%. (Miller et al., 1986). Overall, the proportion of total sunflower seed P in the kernel and hull is approximately 96 and 4%, respectively (Hocking and Steer, 1983a).

Phosphorus has been shown to contribute to increased sunflower plant height, leaf area, and stem diameter (Reddy and Mohammed, 2000; Tomar et al., 1997; Kumar et al., 1995; Mishra et al., 1994; Guar et al., 1973). Stem diameter can increase with increasing P from 9.3 mm to 9.9, 13.1, and 15.7 mm for two, six, and 18 times the P rate (0.08, 0.24, and 0.72 g) in a pot study done by Abbadi, (2011). Dry matter of leaves, stems, and heads and seed can increase with P additions (Reddy et al., 1997; Mishra et al., 1995; Shelke et al., 1988; Reddy and Reddy, 1975); leaf, stem, and head dry matter was increased from 11.8, 16.0, and 14.4 g to 26.1, 44.8, and 30.3 g with addition of 18 times the P rate (0.04 to 0.72 g) (Abbadi, 2011). Sunflower seeds per head (Abbadi, 2011; Khokani et al., 1993; Megur et al., 1993) and oil concentration (Abbadi, 2011; Mishra et al., 1995) has also been found to be influenced positively by P additions. Phosphorus deficiency of sunflower can result in decreased leaf area, leaf number, and leaf expansion, as well as depressed formation of seeds resulting in reduced seed size and seed number (Fageria, 2009; Mengel et al., 2001; Halsted and Lynch, 1996; Lynch et al., 1991).

Uptake of P by sunflower is primarily dependent on thorough root exploration (Connor and Hall, 1997) and is aided by symbiotic association with vesicular arbuscular mycorrhizae (VAM) (Thompson, 1987; Koide, 1985) which increases the acquisition of P from the soil such that sunflower can recover from P deficiency (Hunter et al., 1988). The fungal hyphae of VAM provide considerable extension to the root system into greater soil volumes, and allows sunflower to take up P that is otherwise physically or chemically inaccessible (Connor and Hall, 1997). The degree of VAM associations with sunflower roots is inversely related to soil P levels (Koide, 1985). Soil test analysis as a basis for recommending P fertilizer application can be complicated by VAM as when these fungi are active even a low (6 mg kg^{-1}) concentration of soil P would be adequate for sunflower (Hibberd et al., 1991), while Hunter (1990) found that sunflower not infected with VAM would not grow with <23 mg kg^{-1} of bicarbonate-extractable P. Sunflower P uptake is important in the early phases of growth (Hocking and Steer, 1983a; Hocking and Steer, 1983b; Vrebalov et al., 1980) but uptake will continue during seed filling if it is available in the soil (Hocking and Steer 1983a; Vrebalov, 1974).

Phosphorus requirements and responses

Sunflower requirements and responses to P have been studied much less than N in the northern Great Plains and for sunflower production in general. In North Dakota, Zubriski and Zimmerman (1974) found that P treatments of 0 and 20 kg P ha^{-1} yielded insignificant ($P < 0.05$) values of 2,643 and 2,742 kg ha^{-1}, respectively, as well as identical oil concentrations (46.6%). Zubriski and Zimmerman (1974) concluded that the response of sunflower to P fertilizer was poorly correlated with P soil tests. Sundoz (1984) conducted some of the most extensive work on P in sunflower production for not only North Dakota but also the northern Great Plains and observed no significant ($P < 0.05$) differences in sunflower seed yield or oil concentration with additions of 0, 17, or 34 kg P ha^{-1}. Results obtained by Sundoz indicated that there was no correlation between P soil test and response of sunflower seed and oil yield to P fertilizer, and also that the sunflower plant was able to obtain sufficient supplies of P from soil sources.

Another early study on P in sunflower by Blamey and Chapman (1980) contrasted results from Zubriski and Zimmerman (1974) and Sundoz (1984) with findings that in soils with very low soil P levels a greater response to P was obtained in sunflower than to N fertilizers. Blamey and Chapman (1980) also observed increased sunflower seed oil concentration with higher P levels. In a more recent study, Salih (2013) also observed different findings than Zubriski and

Zimmerman (1974) and Sundoz (1984) finding that P treatments of 0, 20, 40, and 80 kg P ha^{-1} yielded 898, 2180, 3144, and 3884 kg ha^{-1}, respectively, and that increasing P treatments increased sunflower seed oil concentration. Sunflower responses to P observed by Zubillaga et al., (2002) and Geleta et al., (1997) are in agreement with earlier North Dakota studies such that oil concentrations of 50.5, 49.5, and 49.5% for P treatment rates of 0, 12, and 40 kg P ha^{-1} were not significant ($P < 0.05$) (Zubillaga et al., 2002), while Geleta et al., (1997) did not find any significant ($P< 0.05$) differences in sunflower seed yield or oil concentration with P treatments of 0 and 77 kg P_2O_5 ha^{-1}.

A larger range of P treatments, 10, 20, 30, 40, 50, and 60 kg P_2O_5 ha^{-1} have also been investigated for sunflower, resulting in significantly increased yields but no response of sunflower oil concentration (Sadozai et al., 2013). Muralidharudu et al., (2003) found no effect of P fertilization on sunflower seed oil concentration with P_2O_5 rates of 0, 15, 30, 45, 60, and 75 kg ha^{-1} on soils with low (4.4 mg kg^{-1}) , medium (10.7 mg kg^{-1}), or high (17.9 mg kg^{-1}) available P. Sunflower yield was also shown to increase significantly ($P < 0.05$) on these soils up to 60 kg P_2O_5 ha^{-1} in low P soils, and up to 75 and 45 kg P_2O_5 ha^{-1} in medium and high P soils, respectively (Muralidharudu et al., 2003). Sunflower oil concentration also showed no response with an increase in P levels in studies performed by Amanullah Jr et al., (2010), Soleimanzadeh (2010), and Lewis et al., (1991), while sunflower yield was shown to increase significantly with application of P by Sarkar et al., (1995).

Nitrogen and Phosphorus Sources

Sunflower can utilize either nitrate (NO_3^-) or ammonium (NH_4^+) inorganic forms of N, of which, NO_3^- is the main form taken up by roots (Hocking and Steer, 1982). The most important inorganic P ions in soil solution are orthophosphates, HPO_4^{2-} and $H_2PO_4^-$, which are available to sunflower and are found in equal proportions at pH 7, a greater proportion of HPO_4^{2-} when pH is greater than 7 and a greater proportion of $H_2PO_4^-$ when soil pH is less than 7 (Mengel et al., 2001). Nitrogen and P are supplied to sunflower primarily through synthetic N- and P-containing fertilizers, natural processes, and manures. Industrial fixation of atmospheric N_2 based on the Haber-Bosch process produces anhydrous ammonia (NH_3) which may be used directly as a fertilizer or as a substrate to produce urea, NH_4NO_3 ($N_2H_4O_3$), and other synthetic N-containing fertilizers (Havlin et al., 2005). Synthetic P fertilizers include NH_4^+ polyphosphate, Ca phosphates, and NH_4^+ phosphates. Organic N and organic P can come from decomposing crop residues, decaying cover crops, or composts, as well as animal manures, and are not available for sunflower uptake until conversion within the soil through mineralization. Animal manures are primarily a source of organic N and inorganic P, which can represent up to 99% of total N and >75% of total P content (Eghball, 2003; Sharpley and Moyer, 2000; Chadwick et al., 1999).

Nitrogen and Phosphorus Recommendations

When sunflower fertility research was in its early stages in the northern Great Plains, the guide to fertilizing sunflower, presented by Wilkins and Swallers (1972), included that sunflowers “yield best on fertile soil” and that “research data from the area suggest that fertilizer requirements…for producing sunflowers are similar to the requirements of soils seeded to small grains.” The latest Sunflower Production Guide (Berglund, 2007) from North Dakota State University incorporates the same soil fertility principles. According to this most recent guide, a sunflower yield of 2,240 kg ha^{-1} requires approximately the same amount of N and P as about 2,700 kg ha^{-1} of wheat (112 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1}) (Franzen, 2007). Recommendations for N and P after Wilkins and Swaller (1972) soon shifted to a yield-based formula approach as

Dahnke et al., (1981) published a formula for recommending N fertilizer application in North Dakota:

$$\text{N fertilizer} = 0.05 \times \text{YG} - (\text{NO}_3^- - \text{N}_{0\text{-}60}) \qquad \text{(Eq. 1)}$$

in which YG is the yield goal of sunflower (kg ha^{-1}) and (NO_3^- - $N_{0\text{-}60}$) represents the residual NO_3^- present in the soil for a depth of 0 to 60 cm (kg ha^{-1}) from a pre-plant soil test, and this formula is still used to recommend N fertilizer for sunflower with an additional N credit from previous crop (PCC) considered (Franzen, 2010). For P, Dahnke et al., (1992) published a formula for P fertilizer recommendation as

$$\text{P fertilizer} = (0.0225\text{-}0.0014\ \text{STP})\text{YG} \qquad \text{(Eq. 2)}$$

where STP is the soil test P level (mg kg^{-1}) and YG is the sunflower yield goal (kg ha^{-1}), and this formula, like the N formula, is currently utilized in North Dakota for fertilizer recommendations (Franzen, 2010). In each of the formulas for fertilizer recommendation of N and P, soil testing is a necessity. The main components of soil testing for soil fertility purposes include extraction of part of the total nutrient content that is related to, but not equal to, the quantity of plant available nutrients (Havlin et al., 2005). Soil sample analysis in order to obtain values of nutrients, therefore, results in an index of relative nutrient status. As soil test levels decrease below previously defined levels for sunflower in a particular soil or region, nutrient rate recommendations for maximizing yield potential increase. Soil tests for sunflower are conducted prior to planting in the northern Great Plains and to the 15 cm depth for STP and at least the 60 cm depth for NO_3^- -N (Hergert, 1987). In general, soil testing consists of measuring, for example, NO_3^- -N in some portion of the crop rooting zone and crediting this N against the total N needs (Gelderman and Beegle, 1998).

Soil testing is only of value in sunflower production if calibration to sunflower and soil is performed. Without the background of information on sunflower response as related to soil levels of plant nutrients, the values for extracted nutrients have little meaning (Evans, 1987). Soil test calibration is the process of determining the meaning of a soil test measurement in terms of crop response (Dahnke and Olson, 1990). Calibrating the soil test value related to its effect on some desirable crop characteristic, usually yield of marketable product, has been historically involved in the development of a soil test (Corey, 1987). A properly calibrated soil test should provide information in two categories: (i) identify the degree of deficiency or sufficiency of a nutrient and (ii) identify how much of the nutrient should be applied if it is deficient (Havlin et al., 2005; Evans, 1987). Collection of field calibration data for soil tests was a major research activity when soil testing programs began during the middle of the 20th century (Hanway, 1963; Hanna and Flannery, 1960). Although not as common today, it is still widely recognized that calibrations need continual updating and reevaluation (Heckman et al., 2006; Peck and Soltanpour, 1990). In calibration experiments, it is necessary to have the nutrient values covering a range from deficient to sufficient in order to establish a relative yield curve (Evans, 1987) so critical levels for nutrients can be established. Yield normally increases until a point is reached where the main nutrient being tested is not limiting and the yield curve plateaus, which is the critical level for the nutrient pertaining to that crop. The soil test critical level is the soil test value that also produces the best separation between soils that give a yield response for a given crop from those that do not (Beegle, 2005; Black, 1993).

In North Dakota, sunflower N and P calibration and critical levels were established based on sunflower fertility trials conducted annually beginning in 1971 and totaling 32 dryland field trials by 1983 (Zubriski and Morghan, 1983). During this same time, the results of limited N and

P rate studies from Manitoba, Minnesota, and Georgia were also published on how fertilizers affected yield and oil concentration of sunflower (Massey, 1971; Robinson, 1973a; Robinson, 1973b; Soine, 1970; Zubriski and Zimmerman, 1974). The current soil fertility recommendations for sunflower in North Dakota reflect the early research on N and P requirements and subsequent calibration and critical levels (Franzen, 2010). The N and P requirements of sunflower are given by 0.05 and 0.0225 kg N or P per kg sunflower yield (kg kg^{-1}) as part of the N and P yield-based formulas, and these values were previously determined through the early research in North Dakota (Zubriski et al., 1979; Cheng and Zubriski, 1978; Zubriski and Zimmerman, 1974).

In other sunflower producing regions, Minnesota, South Dakota, the High Plains, and in Canada, sunflower N recommendations are commonly in a similar formula format as in North Dakota while P recommendations are based on interpretation of soil test levels of P corresponding to P_2O_5 fertilizer application rates and whether or not fertilizing the soil or the crop is utilized (Beegle, 2005). Minnesota and South Dakota sunflower N and P recommendations follow the same guidelines as in North Dakota, with credits for NO_3^- -$N_{0\text{-}60}$, PCC, and STP and the same calibrated requirements of sunflower (0.05 and 0.0225 kg kg^{-1}) (Kaiser et al., 2011; Gerwing and Gelderman, 2005). Therefore, the northern Great Plains states of North Dakota, South Dakota, and Minnesota are directed in N and P fertilizing by recommendations that reflect the early research determining N and P requirements in North Dakota.

The High Plains recommendation uses N credits similar to the northern Great Plains of PCC and NO_3^- -$N_{0\text{-}60}$, but also includes adjustments for recommended N fertilizer rate of soil texture, previous years' manure, and estimate N mineralized from organic matter (Vigil, 2009). Upon results from a 7-year study in the High Plains, previously calibrated sunflower N requirement of 0.05 kg kg^{-1} was replaced by 0.065 kg kg^{-1} (Vigil, 2009). Originally, Vigil et al., (2001) concluded that 0.05 kg kg^{-1} was the N requirement of sunflower and this N requirement recommendation was confirmed, but more recent research has indicated that a 1,120 kg ha^{-1} sunflower yield requires between 67 and 78 kg N ha^{-1} (Table 3). The P recommendation in the High Plains uses the same soil test level interpretations as the northern Great Plains, however, the values are estimated for P_2O_5 fertilizer application rates. In Canada, the published sunflower fertilizer recommendations for N indicate a curvilinear yield response to N, which is dictated by the NO_3^- -$N_{0\text{-}60}$. A NO_3^- -$N_{0\text{-}60}$ of 22 kg results in an N recommendation of 67 kg N for 1,960 kg ha^{-1} yield (0.034 kg kg^{-1}) and 213 kg N for 2,800 kg ha^{-1} yield (0.076 kg kg^{-1}), while a NO_3^- -$N_{0\text{-}60}$ of 56 kg results in an N recommendation of 0 kg N for 1,750 kg ha^{-1} yield (0.029 kg kg^{-1}) and 168 kg N for 2,800 kg ha^{-1} yield (National Sunflower Association of Canada, 2012). This curvilinear response to N fertilizer rate incorporates the diminishing returns of N per kg of sunflower yield at higher yields and N rates, and is opposed to the linear response assumed in N recommendation formulas for the High Plains and northern Great Plains of the U.S. Phosphorus fertilizer recommendations in Canada (National Sunflower Association of Canada, 2012) are similar to the High Plains (Vigil, 2009), providing estimates of P_2O_5 fertilizer rates, while also using the same soil test interpretation levels of P to dictate response of sunflower to the addition of fertilizer.

INTRODUCTION

Currently, sunflower production in the northern Great Plains states of Minnesota, North Dakota, and South Dakota of the U.S. represents nearly 85% of the total sunflower production in the U.S. and North Dakota represents approximately 40% alone (USDA-NASS, 2015). Although sunflower production has generally declined since the 1970s in the U.S. (Sandbakken and Kleingartner, 2007), sunflower is still one of the most important annual crops grown for edible oil in the world (Putt, 1997) and is a mainstay in agricultural production systems in the northern Great Plains (USDA-NASS, 2015). Because of the importance of sunflower, improvements have continued to be made to the production of and the crop itself, and the evolution of sunflower in the last 40 years has resulted in greater yield potentials (Hulke and Kleingartner, 2014). However, the improvements in sunflower production have not been associated with fertility requirements in the northern Great Plains, and therefore, relating the evolution of sunflower to fertility requirements is needed. The current N and P recommendations and calibrated N and P requirements and critical levels used in the northern Great Plains reflect the early research when commercial cultivation of sunflower first began in the 1970s. Using the current N and P recommendations in the northern Great Plains may limit the improvements that have increased yield potentials. Therefore, objectives of N and P recalibration in this study are to develop modern N and P recommendations that reflect the evolution of sunflower production and the sunflower seed itself through documented responses of sunflower yield and sunflower oil concentration to N and P fertilizer rates in the northern Great Plains.

MATERIALS AND METHODS

Site-Years and Fertilization Methods

Nitrogen and P rate trials with confectionary and oilseed sunflower were taken to yield on a total of 23 sites in North Dakota in both 2014 and 2015 (Tables 4 and 5). Each trial was established with cooperating farmers within their commercial-sized fields. Cooperators planted each trial with a sunflower type (confectionary or oilseed) and hybrid of their choice and made appropriate applications of pesticides for weed, disease, and insect control to the experimental area when application to the entire field was performed. No additional fertilizer N or P was applied within the trial area by the cooperator. The experimental design for each trial location was a randomized complete block arranged as a split plot with four replications, with N rate as main plot and P rate as the split treatment.

Nitrogen treatments in 2014 and 2015 were check (no added N), 45, 90, 134, 179, and 224 kg N ha^{-1} (indicated as N rate in Results and Discussion sections). Nitrogen fertilizer was applied by hand, pre or post plant within a week of planting, in 2014 as either ammonium nitrate or Agrotain® treated urea and in 2015 as either ammonium nitrate or Limus® treated urea. Treatments were incorporated by the cooperator in conventional tillage sites within a week of application. In no-tillage sites, the N fertilizer was surface applied with no mechanical incorporation. Within the main plots in 2014, four P treatment rates were applied in the subplots; check (no added P), 34, 67, and 101 kg P_2O_5 ha^{-1} (indicated as P rate in Results and Discussion sections). Two P treatment rates were applied in the subplots in 2015; check (no added P) and 67 kg P_2O_5 ha^{-1}. Phosphorus fertilizer was applied in 2014 and 2015 as triple superphosphate by hand pre or post plant within a week of planting. At conventional tilled sites, the P was incorporated along with the N treatments within a week following application. In 2015, at the time of N and P fertilizer application, 22 kg S ha^{-1} was also applied to each trial location as gypsum granules (112 kg gypsum ha^{-1}).

Each experimental unit (subplot) was 9.1 m in length and 3.05 m in width. Row width of each site and GPS coordinates are listed in Tables 4 and 5. Composite soil samples from eight soil cores obtained at the 0-15 cm and 15-60 cm depths were collected at each trial location in each year before fertilizer application to determine NO_3^- - $N_{0\text{-}60}$, available soil K, plant available P, and other relevant soil chemical properties. Soil test results for each site-year are listed in tables in the appendix.

Growing Season Plot Maintenance

Replications were separated at each trial location by either a 150 cm or 300 cm alleyway which had no fertilizer applied. Alleyways were cleared of growing sunflowers between the V4-V6 (four or six leaf stage of sunflower) vegetative growth stages. There was also a buffer zone of growing sunflowers without application of fertilizer, between 150 cm and 300 cm in width, around the outside of each trial area to prevent errant N or P fertilizer from the field fertilizer application from entering the experimental treatment areas. Weeds were removed by hand, if necessary, at V4-V6, V12, and later growth stages from the trial area. Any disease and insect prevalence was noted at V4-V6, V12, and later growth stages.

Table 4. North Dakota 2014 location and soil background information.

Year	Location	GPS coordinate (NW site corner)	Soil type	Tillage[†]	Previous crop
2014	Amidon	46°19'26.912"N 103°23'34.870"W	Golva silt loam	no-tillage, long-term	wheat
	Beach	46°49'02.928"N 103°59'35.290"W	Sen-Golva silt loam	no-tillage, long-term	wheat
	Belfield	47°04'52.539"N 103°09'53.605"W	Lihen-Parshall complex loamy sand	no-tillage, long-term	wheat
	Cummings	47°30'43.150"N 97°06'44.884"W	Glyndon silt loam	conventional tillage	corn
	Dickinson North	47°03'53.825"N 102°50'37.729"W	Regent-Janesburg complex silty clay loam	no-tillage, long-term	corn
	Dickinson South	46°43'42.114"N 102°48'38.101"W	Lawther-Daglum complex silty clay	no-tillage, long-term	corn
	Hazelton	46°20'21.252"N 100°11'30.253"W	Amor-Werner loams	no-tillage, long-term	corn
	Hazen	47°29'28.192"N 101°30'14.330"W	Williams-Bowbells loams	no-tillage, long-term	wheat
	Heil	46°20'31.580"N 101°41'01.112"W	Vebar-Parshall fine sandy loams	no-tillage, long-term	wheat
	Valley City	46°52'58.010"N 97°54'53.505"W	Barnes-Svea loams	no-tillage, long-term	wheat
	Walcott	46°29'10.505"N 97°03'10.231"W	Glyndon loam	conventional tillage	corn

[†] Long-term no-tillage are fields that have been in a no-tillage system for six or more years.

Table 5. North Dakota 2015 location and soil background information.

Year	Location	GPS coordinate (NW site corner)	Soil type	Tillage[†]	Previous crop
2015	Amenia	47°02'05.939"N 97°11'38.605"W	Galchutt-Fargo silty clay loams	conventional tillage	soybean
	Amidon	46°19'26.995"N 103°21'53.946"W	Chama-Cabba silt loams	no-tillage, long-term	wheat
	Beach	46°51'12.289"N 103°55'29.614"W	Chama-Cabba-Sen silt loams	no-tillage, long-term	wheat
	Belfield	47°03'08.192"N 103°14'05.589"W	Belfield-Grail clay loams	no-tillage, long-term	wheat
	Bottineau North	48°49' 19.524"N 100°42' 59.213"W	Barnes-Svea-Tonka complex loams	no-tillage, long-term	wheat
	Bottineau South	48°49' 13.625"N 100°42' 41.111"W	Barnes-Svea-Tonka complex loams	no-tillage, long-term	wheat
	Coleharbor	47°31'49.819"N 101°16'41.822"W	Williams-Bowbells loams	strip-tillage	corn
	Dickinson	46°59'43.425"N 102°46'40.872"W	Amor-Cabba loams	no-tillage, long-term	corn
	Elgin	46°26'34.239"N 101°54'02.755"W	Lawther silty clay	no-tillage, long-term	wheat
	Linton	46°13'01.639"N 100°03'50.523"W	Straw silt loam	no-tillage, long-term	soybean
	Valley City	46°52'36.844"N 97°56'24.370"W	Fordville loam	no-tillage, long-term	wheat
	Walcott	46°35'16.441"N 97°02'55.626"W	Hecla-Garborg fine sandy loams	conventional tillage	corn

[†] Long-term no-tillage are fields that have been in a no-tillage system for six or more years.

Table 6. North Dakota 2014 soil test results.

Year	Location	Depth (centimeters)	NO_3-N[†] (kg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH	EC[‡] (dS m^{-1})	OM[§] (g kg^{-1})
2014	Amidon	0-15	9	5	250	8.0	0.23	33
		15-60	34	/[¶]	/	/	/	/
	Beach	0-15	12	14	280	6.0	0.12	31
		15-60	20	/	/	/	/	/
	Belfield	0-15	15	17	260	6.2	0.10	30
		15-60	24	/	/	/	/	/
	Cummings	0-15	27	21	145	7.8	2.09	40
		15-60	178	/	/	/	/	/
	Dickinson North	0-15	/	32	/	/	/	/
		0-60	149	/	/	/	/	/
	Dickinson South	0-15	11	8	242	6.3	0.27	26
		15-60	20	/	/	/	/	/
	Hazelton	0-15	/	19	385	5.7	0.26	52
		0-60	85	/	/	/	/	/
	Hazen	0-15	18	18	265	6.8	0.37	40
		15-60	74	/	/	/	/	/
	Heil	0-15	35	9	250	7.8	0.30	42
		15-60	81	/	/	/	/	/
	Valley City	0-15	/	14	/	/	/	/
		0-60	32	/	/	/	/	/
	Walcott	0-15	/	12	190	8.2	/	/
		0-30	68	/	/	/	/	/

[†] Total NO_3-N represents NO_3^- - N_{0-60}, except for Walcott 2015 (NO_3^- - N_{0-30}).

[‡] Electrical conductivity.

[§] Organic matter.

[¶] No data.

Table 7. North Dakota 2015 soil test results.

Year	Location	Depth (centimeters)	NO_3-N[†] (kg ha^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	pH	EC[‡] (dS m^{-1})	OM[§] (g kg^{-1})
2015	Amenia	0-15	/[¶]	28	396	7.3	0.44	55
		0-60	63	/	/	/	/	/
	Amidon	0-15	/	3	/	/	/	/
		0-60	40	/	/	/	/	/
	Beach	0-15	/	2	113	8.1	0.25	26
		0-60	45	/	/	/	/	/
	Belfield	0-15	/	8	148	6.4	0.13	25
		0-60	54	/	/	/	/	/
	Bottineau North	0-15	17	7	430	7.8	/	52
		15-60	20	/	/	/	/	/
	Bottineau South	0-15	20	8	465	7.5	/	49
		15-60	27	/	/	/	/	/
	Coleharbor	0-15	29	8	250	6.2	0.27	41
		15-60	72	/	/	/	/	/
	Dickinson	0-15	/	6	122	5.9	0.17	34
		0-60	94	/	/	/	/	/
	Elgin	0-15	/	12	325	5.8	0.26	56
		0-60	94	/	/	/	/	/
	Linton	0-15	4	7	290	6.9	0.28	44
		15-60	24	/	/	/	/	/
	Valley City	0-15	/	21	135	6.2	/	31
		0-60	26	/	/	/	/	/
	Walcott	0-15	/	11	95	6.2	0.10	15
		0-60	94	/	/	/	/	/

[†] Total NO_3-N represents NO_3^- - N_{0-60}.

[‡] Electrical conductivity.

[§] Organic matter.

[¶] No data.

Table 8. North Dakota 2014 sunflower crop information.

Year	Location	Planting date	Seed type	Cultivar	Oil type[†]	Row width	Harvest date
						— cm —	
2014	Amidon	23-May	oilseed	Mycogen 8H288CLDM	high-oleic	76	2-Oct
	Beach	4-Jun	oilseed	Pioneer P63ME80/N472	mid-oleic	76	10-Oct
	Belfield	31-May	oilseed	Mycogen 8H288	high-oleic	76	2-Oct
	Cummings	8-Jun	confectionary	Royal Hybrid 1121	NA[§]	76	21-Oct
	Dickinson North	5-Jun	confectionary	Red River 2215	NA	76	9-Oct
	Dickinson South	8-Jun	oilseed	Pioneer P63ME80	mid-oleic	76	9-Oct
	Hazelton	1-Jun	oilseed	/[‡]	NA	76	29-Sep
	Hazen	4-Jun	oilseed	Pioneer P63HE60	high-oleic	/	12-Oct
	Heil	10-Jun	oilseed	Croplan 3080	mid-oleic	76	9-Oct
	Valley City	20-May	oilseed	Syngenta 3495CLDM	mid-oleic	76	23-Sep
	Walcott	31-May	confectionary	Royal Hybrid 400CL	NA	76	26-Sep

[†] Mid-oleic oil type refers to NuSun® sunflower oil.
[‡] No information.
[§] Not applicable.

Table 9. North Dakota 2015 sunflower crop information.

Year	Location	Planting date	Seed type	Cultivar	Oil type[†]	Row width	Harvest date
						— cm —	
2015	Amenia	11-Jun	oilseed	NK 7111	high-oleic	56	15-Oct
	Amidon	26-Apr	oilseed	Mycogen 8H288 CLDM	high-oleic	76	21-Sep
	Beach	21-May	oilseed	Pioneer P63HE60/N393	mid-oleic	76	22-Sep
	Belfield	11-May	oilseed	Mycogen 8H 2888	high-oleic	76	21-Sep
	Bottineau North	29-May	oilseed	Mycogen 288	high-oleic	76	8-Oct
	Bottineau South	30-May	oilseed	Mycogen 288	high-oleic	76	8-Oct
	Coleharbor	15-Jun	oilseed	Mycogen 288	high-oleic	76	15-Oct
	Dickinson	30-May	confectionary	Red River 2215	NA[‡]	76	6-Oct
	Elgin	26-May	oilseed	Croplan 3080	mid-oleic	76	1-Oct
	Linton	30-May	oilseed	Pioneer 63HE60	high-oleic	76	29-Sep
	Valley City	4-Jun	oilseed	Syngenta 3495CLDM	mid-oleic	76	7-Oct
	Walcott	31-May	confectionary	Royal Hybrid 400CL	NA	76	26-Sep

[†] Mid-oleic oil type refers to NuSun® sunflower oil.

[‡] Not applicable.

Sunflower Yield and Quality Data

One of the middle rows of sunflower heads from each subplot was harvested by hand by clipping the head from the stalk as close to the head as possible, and putting into burlap bags. The outside sunflower heads at each end of the row were not harvested. Stand was counted from alley to alley within the row. Lodged sunflowers, defined as sunflowers leaning more than a 45 degree angle, were also counted at harvest. Harvest dates of each North Dakota site-year are listed in Tables 3 and 4. Sunflower heads were oven dried at 30 to 40 °C to a moisture between 8 and 10 percent prior to being threshed. Threshing of sunflower heads was conducted using a 1985 Hege® plot combine in 2014 and an Almaco® (Almaco® Nevada, Iowa, USA) low profile plot thresher in 2015.

Sunflower seed grain yield was determined using an electronic Sartorius® weighing scale to the nearest 0.1 g. Moisture and test weight were determined on a seed grain subsample using a Dickey-John GAC500XT® moisture and test weight meter (Dickey-John, Auburn, IL, USA). Yields were adjusted to 10 percent moisture across all site-years. A nuclear magnetic resonance (NMR; MQC, Oxford Instruments, Abingdon, Oxfordshire, United Kingdom) oil test was applied to all high oleic or NuSun oilseed sunflower seeds (kernel plus hull) (Tables 8 and 9), at the USDA Sunflower Testing Center, Fargo, North Dakota, to obtain the oil percentage adjusted to 10 percent moisture.

Statistical Data Analysis

Statistical analysis was conducted using SAS 9.3 for Windows (SAS Institute, Inc., 2013). The routine PROC GLM was used to perform analysis of variance (ANOVA) to determine the effect of N application, P application, and N by P interaction on sunflower yield and quality data. Yield and quality means were grouped based on LSD. The N and P treatments were differentiated using a p-value of 5 percent probability. Regression analyses to determine the best-predicting model relation sunflower yield, oil concentration, or lodging with N rates were performed using Microsoft Excel. In these analyses, the dependent variable was sunflower yield, oil concentration, or lodging, and the independent variable was the N fertilizer treatment rate plus the NO_3^- - $N_{0\text{-}60}$, giving a value for total known available N. Following preliminary analyses, a quadratic polynomial ($y=ax^2+bx+c$) regression model was generally found to have the greatest coefficient of determination (r^2) between sunflower yield (Y) and total known available N (X). Exceptions to this were linear ($y=ax+b$) responses for three site-years sunflower yield analysis. Sunflower oil concentration was described by a linear regression model, with only two exceptions in the dataset. Therefore, quadratic polynomial models and linear models are presented throughout this thesis describing responses of sunflower yield and sunflower oil concentration to total known available N.

Regression analysis for each site-year was done using average yields of N rate treatments as the dependent variable. Multiple regression analysis was performed in Microsoft Excel to determine whether the data should be categorized into regional and sunflower seed type (confectionary or oilseed) sites for improved relationships between sunflower seed yield and total known available N. This analysis used normalized yields from individual site-years inserted into a generalized yield equation (TRT = treatment):

Normalized regional or seed type yield = (TRT average yield for site-year/highest TRT average yield for site-year) *regional or seed type average yield (Eq. 3)

Results indicated that segregation between eastern and western North Dakota, no-tillage and conventional tillage, and oilseed and confectionary sunflower site-years improved relationships and is therefore presented in this thesis. Analysis was performed on the basis of updating N recommendations for sunflower, and improved relationships for regional and seed type dictate these rather than individual site analysis.

RESULTS AND DISCUSSION FOR OILSEED SUNFLOWER

Amidon 2014 and 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 and 2015 Amidon yield and oil data, adjusted for 10% moisture, are provided in Table 10 and Table 11, with associated p-values available in Table 12. Sunflower yield increased with N rate in 2014. The addition of 45 kg ha^{-1} of N increased yield from 1,386 to 1,877 kg ha^{-1}, but higher N rates did not result in greater yields over the 45 kg ha^{-1} rate. Nitrogen rate affected oil concentration in 2014, with most N treatments resulting in increased oil concentration, which agrees with results of Mollashahi et al., (2013) and Salih, (2013). The increase in oil was not consistent however, with lower oil concentration obtained with the 135 kg ha^{-1} N rate compared to other N treatments. The 2014 Amidon site had a very large random infestation of downy mildew (*Plasmopara halstedii* (Farl.) Berl. & de Toni) which negatively impacted yields, and influenced yield and oil concentration. Sunflower plants which grew next to downy mildew infected plants compensated for the infected plant's decreased size and growth by having larger heads than would normally be expected. Yield and oil concentration at Amidon in 2015 did not vary with N rate. Amidon 2014 and 2015 was similar in NO_3^- - N_{0-60} (Table 6 and Table 7), however, the mineralization of N in these long-term no-tillage fields was probably different between years and locations to account for the differences in N response.

Except for yield, no significant effect of P application rate was found at Amidon. The soil test P level at Amidon in 2014 was lower than in 2015 (Table 6 and Table 7), but even with low soil test P levels in both years, no consistent response was found. Random occurrence of downy mildew may have contributed to significantly different yields obtained in 2014, since soil test P was relatively similar in both years.

Table 10. Nitrogen rate ANOVA analysis of 2014 and 2015 Amidon oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015	
N rate	**Yield**	**Oil concentration**	**Yield**	**Oil concentration**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**	**%**
0	1386b[†]	39.1b	2435a	40.1a
45	1877a	39.9ab	2512a	39.9a
90	2018a	41.1a	2671a	40.4a
135	1947a	39.3b	2771a	39.1a
180	2199a	41.1a	2645a	39.1a
225	2116a	40.8a	2555a	39.1a

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 11. Phosphorus rate ANOVA analysis of 2014 and 2015 Amidon oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015	
P rate	**Yield**	**Oil concentration**	**Yield**	**Oil concentration**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**	**%**
0	1788b[†]	40.2a	2669a	39.8a
33	1855ab	39.9a		
67	1908ab	40.3a	2527a	39.5a
101	2136a	40.5a		

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 12. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Amidon, 2014 and 2015.

	2014		2015	
Source of variation	**Yield**	**Oil concentration**	**Yield**	**Oil concentration**
N	0.0005	0.0028	0.8219	0.5346
P	0.1069	0.7704	0.3495	0.6032
N x P	0.3907	0.9832	0.2990	0.6967

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 Amidon sunflower of total known available N relationship to yield is presented in Figure 2. Regression analysis of yield results in a quadratic curve with a peak yield at 222 kg N ha^{-1}. The regression model is highly significant with a coefficient of determination (r^2) of 0.89. The regression analysis of Amidon 2014 oil concentration, and Amidon 2015 yield and oil was not significant.

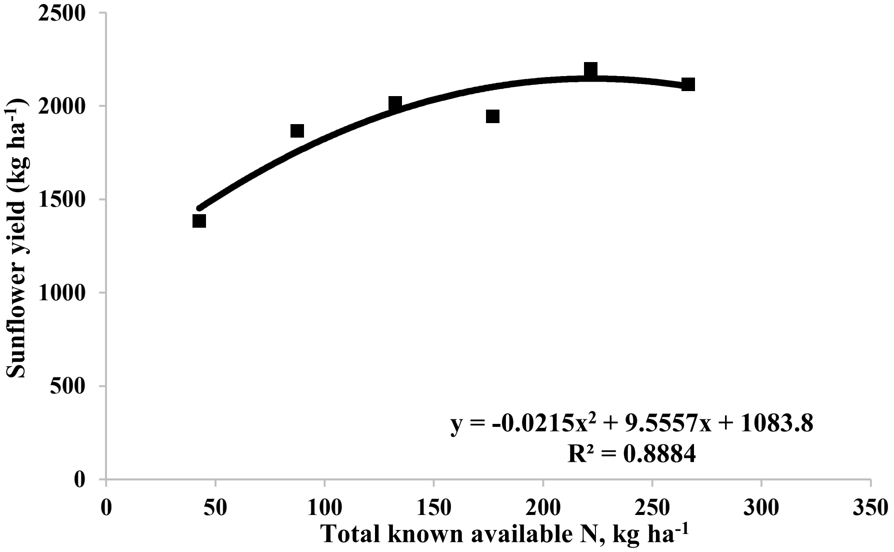

Figure 2. Relationship between total known available N and 2014 Amidon sunflower yield.

Beach 2014 and 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 and 2015 Beach yield and oil data, adjusted for 10% moisture, are provided in Table 13 and Table 14, with associated p-values available in Table 15. In 2014, freezing temperature conditions in early September restricted yield and oil concentration, influencing consistency of responses and resulting in severely reduced values. Sunflower yield and oil concentration increased with N rate in 2014, reaching maximum values at a treatment N rate of 180 kg ha^{-1}. The addition of 225 kg ha^{-1} of N decreased yield significantly from the maximum. Higher yields were obtained in 2015 with increasing N rate, while oil concentration decreased significantly with increasing N rate, which agrees with results of Blamey and Chapman (1980).

No significant influence of P application rate was found in yield or oil content in 2014 or 2015. In 2014, the P soil test indicated a high level (Franzen, 2013) of available P (Table 6), however, in 2015, there was a very low level of P in the soil test (Table 7). Regardless, sunflower did not respond to P in either case, indicating that sunflower was able to extract the P it required, perhaps with the aid of soil mycorrhizal fungi (Hibberd et al., 1991).

Table 13. Nitrogen rate ANOVA analysis of 2014 and 2015 Beach oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		**2015**	
N rate	**Yield**	**Oil concentration**	**Yield**	**Oil concentration**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**	**%**
0	1254c[†]	28.2c	2048d	40.2a
45	1608a	29.5bc	2297cd	39.2ab
90	1532ab	30.7a	2825a	38.4bc
135	1543a	30.9a	2330bcd	37.5cd
180	1565a	30.3ab	2622ab	37.9c
225	1360bc	29.5bc	2566abc	36.8d

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 14. Phosphorus rate ANOVA analysis of 2014 and 2015 Beach oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		**2015**	
P rate	**Yield**	**Oil concentration**	**Yield**	**Oil concentration**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**	**%**
0	1438a[†]	29.3a	2448a	38.4a
33	1489a	29.7a		
67	1437a	30.0a	2447a	38.2a
101	1545a	30.9b		

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 15. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Beach, 2014 and 2015.

Source of variation	2014 Yield	2014 Oil concentration	2015 Yield	2015 Oil concentration
N	0.0008	0.0001	0.0002	<0.0001
P	0.4062	0.0001	0.9866	0.7541
N x P	0.2601	0.5178	0.3648	0.7072

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 and 2015 Beach sunflower with total known available N relationship to yield and oil concentration are presented in Figure 3 through Figure 6. The freezing temperature conditions in 2014 resulted in reduced yields, but the regression model for yield is still highly significant with an r^2 of 0.74. The quadratic curve for 2014 yields peaks at the 150 kg N ha^{-1}, and declines with greater N rates. Sunflower oil concentration in 2014 follows the same significant trend, reaching a peak of 31% near the 150 kg N ha^{-1} rate. A 31% oil concentration is well below the 40% industry standard, and the low oil was the result of the hard freeze in mid-September that arrested sunflower kernel development.

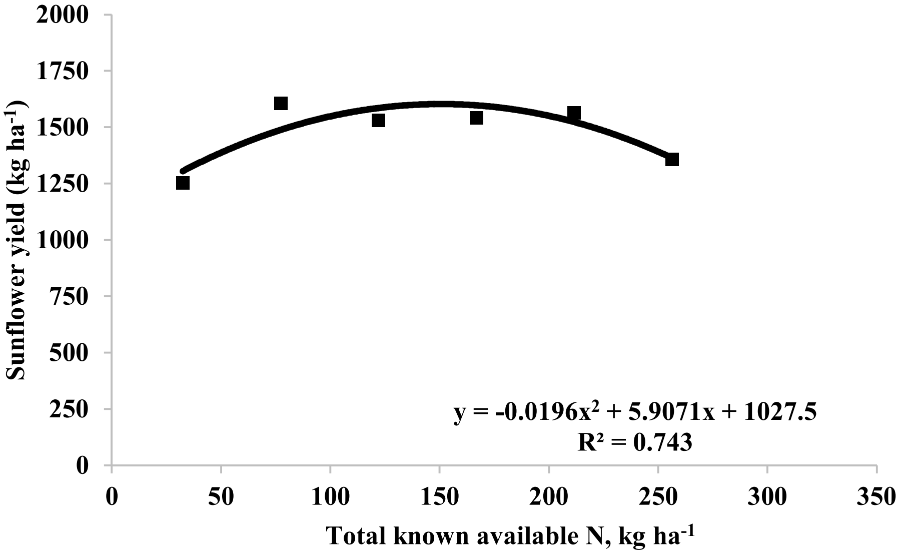

Figure 3. Relationship between total known available N and 2014 Beach sunflower yield.

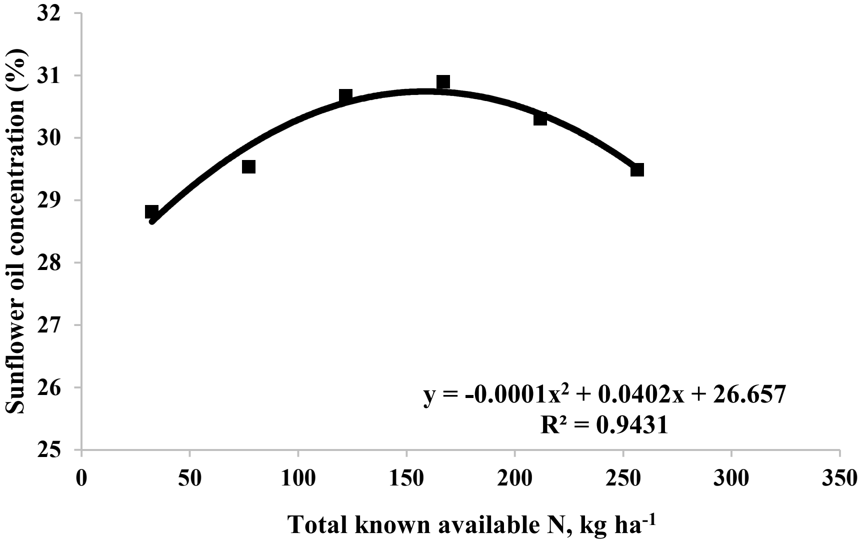

Figure 4. Relationship between total known available N and 2014 Beach sunflower oil concentration.

In 2015, the significant regression model ($r^2 = 0.54$) for yield indicates that 202 kg N ha^{-1} of total known available N resulted in maximum yield of about 2,600 kg ha^{-1}. The highly significant regression model for oil concentration (r^2 of 0.92) shows oil concentration decreasing with N rate. The highest oil concentration was obtained from the check N treatments.

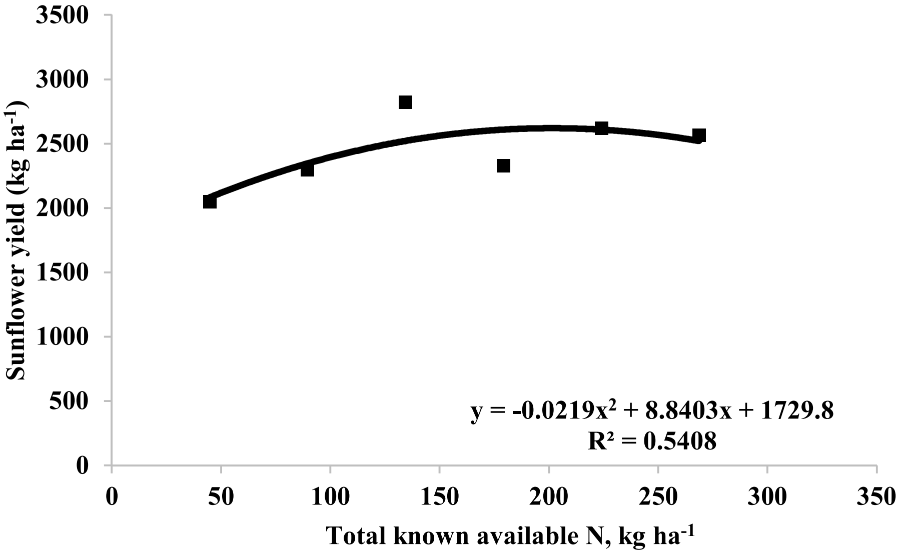

Figure 5. Relationship between total known available N and 2015 Beach sunflower yield.

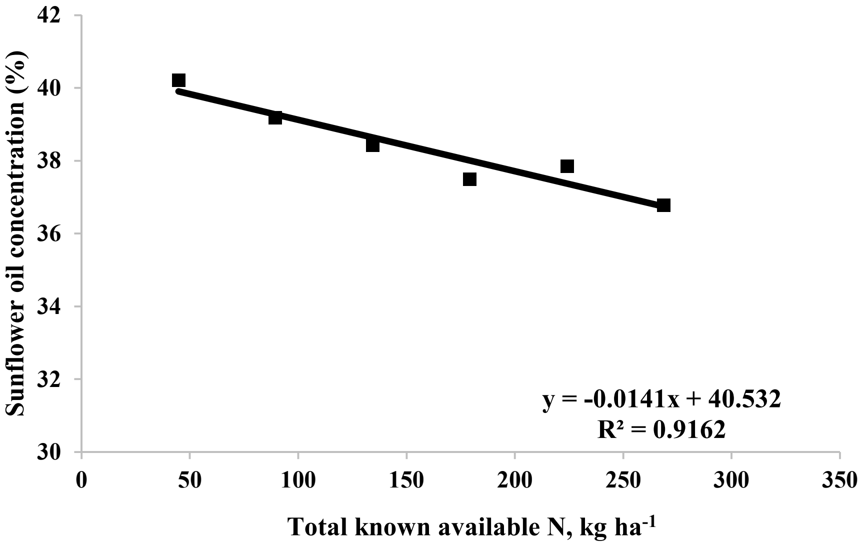

Figure 6. Relationship between total known available N and 2015 Beach sunflower oil concentration.

Regression Analysis – Lodging

Regression analysis for 2015 Beach sunflower with total known available N relationship to sunflower percent lodging is shown in Figure 7. The linear regression was highly significant ($r^2 = 0.92$) for percent lodging and total known available N. Percent lodging was calculated on plant stand counts and lodged plants accounted for within each harvested row. At Beach in 2015, the average plants per row was 31. The number of plants lodged was one, five, seven, 10, 15, and 14 for the check, 45, 90, 135, 180, and 225 kg N ha^{-1}, respectively.

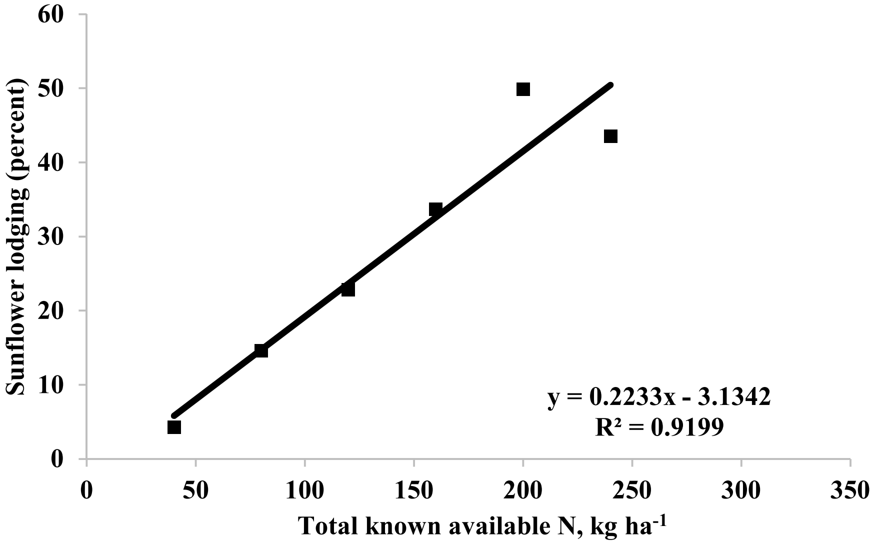

Figure 7. Relationship between total known available N and 2015 Beach sunflower percent lodging.

Belfield 2014 and 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 and 2015 Belfield yield and oil data, adjusted for 10% moisture, are provided in Table 16 and Table 17, with associated p-values available in Table 18. In 2014, sunflower yield increased with N rate, from 1,772 kg ha^{-1} for check N treatments to 2,266 kg ha^{-1} for 180 kg ha^{-1} N treatments. Oil concentration significantly increased between check N treatments and 45 kg ha^{-1} N rate treatments, while the 135, 180, and 225 kg ha^{-1} N treatment rates significantly reduced oil concentration. In 2015 oil concentration decreased with increasing N rate. Yield was not influenced by N rate at Belfield in 2015. It is possible that since the field had not been seeded to sunflower in 5 years, and 2012 was a drought year, that high NO_3^- - N below our sampling depth of 60 cm was present. Significantly reduced oil concentrations were found with the addition of each N rate in 2015. The highest oil concentration (43.3%) was observed in the check N treatments.

Significant effects of P application were found in 2014 for yield and oil concentration, but only with the highest rate of P, 101 kg ha^{-1}. This rate of P increased both yield and oil concentration for Belfield in 2014, however, the response was not economic, considering $1.25 kg^{-1} P_2O_5 ($126.25 cost), and 44 cents kg^{-1} sunflower ($99 gross revenue increase to P). In 2015, yield and oil concentration were not influenced by application rate of P. Soil test P results (Table 6 and Table 7) indicate that conditions in 2015 provided a greater chance of P response than those in 2014.

Table 16. Nitrogen rate ANOVA analysis of 2014 and 2015 Belfield oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015	
N rate	Yield	Oil concentration	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%
0	1772d[†]	40.5cd	2114a	43.3a
45	1931cd	41.5a	2142a	41.9b
90	1992bcd	41.3ab	1835a	40.9ab
135	2035bc	41.1bcd	2163a	40.1cd
180	2266a	40.4d	2151a	39.0d
225	2197ab	40.3d	2001a	39.1d

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 17. Phosphorus rate ANOVA analysis of 2014 and 2015 Belfield oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015	
P rate	Yield	Oil concentration	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%
0	1957b[†]	40.4b	2091a	40.8a
33	1909b	40.7ab		
67	2072ab	41.0ab	2045a	40.6a
101	2192a	41.3a		

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 18. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Belfield, 2014 and 2015.

Source of variation	2014 Yield	2014 Oil concentration	2015 Yield	2015 Oil concentration
N	0.0004	0.0234	0.6056	<0.0001
P	0.0124	0.0583	0.7059	0.5454
N x P	0.1955	0.7856	0.7012	0.6577

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 and 2015 Belfield sunflower with total known available N relationship to yield and oil concentration are presented in Figure 8 through Figure 10. The yield increase with N rate for Belfield in 2014 results in a highly significant regression model for yield with an r^2 of 0.90. Yields attain a plateau at higher N rates. Oil concentration decreases with N rate after reaching a concentration of 41.5% with an N rate of 90 kg ha^{-1}. Sunflower oil concentration of Belfield 2015 steadily decreases with increasing N rate from a maximum of about 43.5%, and has a significant regression model with an r^2 of 0.99.

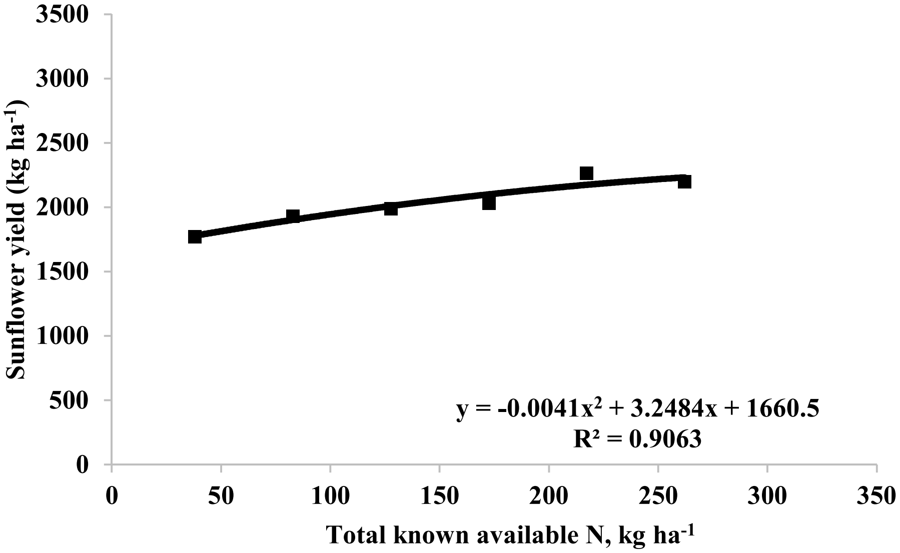

Figure 8. Relationship between total known available N and 2014 Belfield sunflower yield.

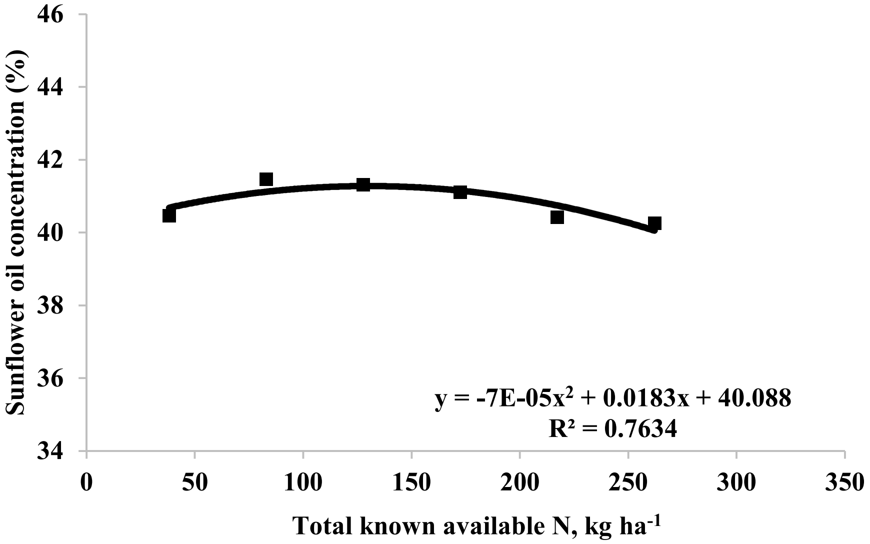

Figure 9. Relationship between total known available N and 2014 Belfield sunflower oil concentration.

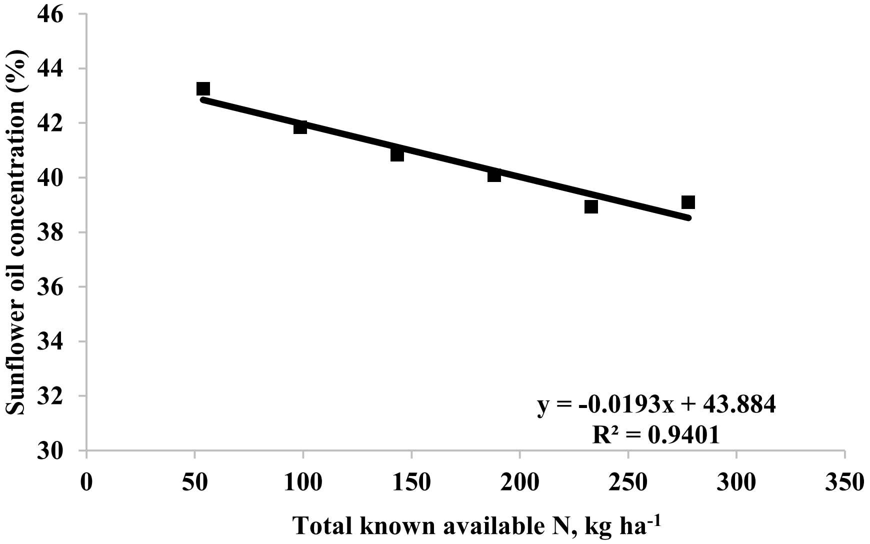

Figure 10. Relationship between total known available N and 2015 Belfield sunflower oil concentration.

Valley City 2014 and 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 and 2015 Valley City yield and oil data, adjusted for 10% moisture, are provided in Table 19 and Table 20, with associated p-values available in Table 21. Sunflower yield increased in 2014 and 2015 with N rate. In 2014, the 135, 180, and 225 kg ha^{-1} N rates increased yield, while in 2015, there was a yield decrease at the 180 kg ha^{-1} rate compared to other N treatments greater than 45 kg ha^{-1}. Sunflowers lodged in 2014 at Valley City due to high winds during a thunderstorm, and the number of lodged plants and the degree of lodging (flat on the ground compared to leaning) was greater in higher N treatment rates, similar to findings by Darby et al., (2013). Although commercially a yield loss is experienced with lodging because of the inability for the combine to secure all of the sunflower heads, in this research, all of the heads were cut and placed in the harvest bag whether they were on the soil surface or on an upright stalk. Increasing N rate resulted in decreased oil concentrations in 2014 and 2015 at Valley City. Oil concentration for check N treatment rates in 2014 and 2015 were 40.7 and 37.3%, respectively, while oil concentration for 225 kg ha^{-1} N treatment rates in 2014 and 2015 were 38.3 and 35.2%, respectively. No effect from P treatment rates was found in 2014 or 2015 at Valley City for yield or oil concentrations. Soil test P levels in 2014 and 2015 were 14 and 21 mg kg^{-1}, respectively (Table 6 and Table 7).

Table 19. Nitrogen rate ANOVA analysis of 2014 and 2015 Valley City oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015	
N rate	Yield	Oil concentration	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%
0	1417c[†]	40.7a	2045b	37.3ab
45	1440c	40.6ab	2544ab	37.4a
90	1594bc	39.5bc	2749a	36.2abc
135	1804ab	39.7abc	2926a	35.6bcd
180	1840a	39.1cd	2413ab	34.1d
225	1603ab	38.3d	2735a	35.2cd

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 20. Phosphorus rate ANOVA analysis of 2014 and 2015 Valley City oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015	
P rate	Yield	Oil concentration	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	%
0	1656a[†]	39.5a	2552a	36.1a
33	1667a	39.6a		
67	1575a	39.7a	2585a	35.9a
101	1567a	39.8a		

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 21. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Valley City, 2014 and 2015.

	2014		2015	
Source of variation	Yield	Oil concentration	Yield	Oil concentration
N	0.0011	0.0003	0.0237	0.0043
P	0.6090	0.9035	0.8222	0.6218
N x P	0.9134	0.7777	0.7227	0.8893

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 and 2015 Valley City sunflower with total known available N relationship to yield and oil concentration are presented in Figure 10 and Figure 11. The regression analysis of 2014 yield with N rate was not significant. The regression model for oil concentration of 2014 Valley City (Figure 10) is highly significant with an r^2 of 0.93, with the maximum of oil concentration obtained from the check.

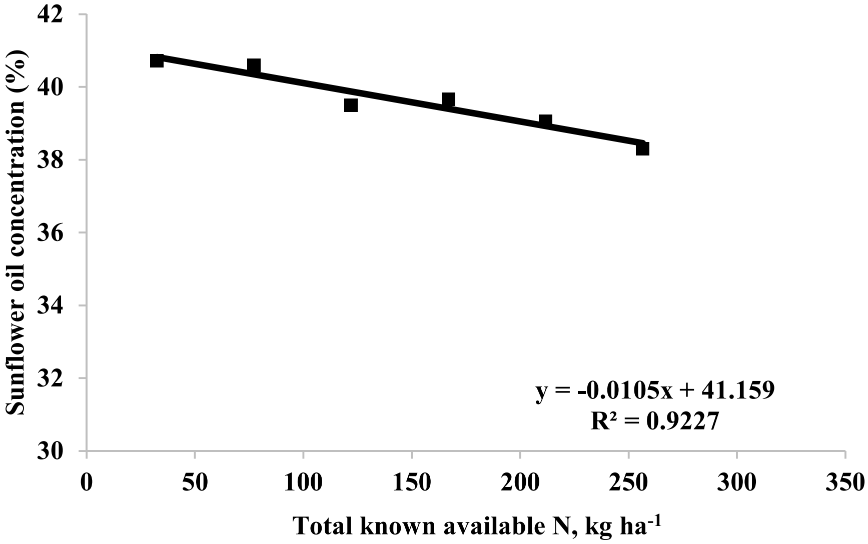

Figure 11. Relationship between total known available N and 2014 Valley City sunflower oil concentration.

Oil concentration for 2015 Valley City sunflowers was highest for the check N treatments, as in 2014 at Valley City. The significant regression model for 2015 Valley City oil concentration has an r^2 of 0.80 (Figure 11) while the regression model for yield in 2015 was not significant.

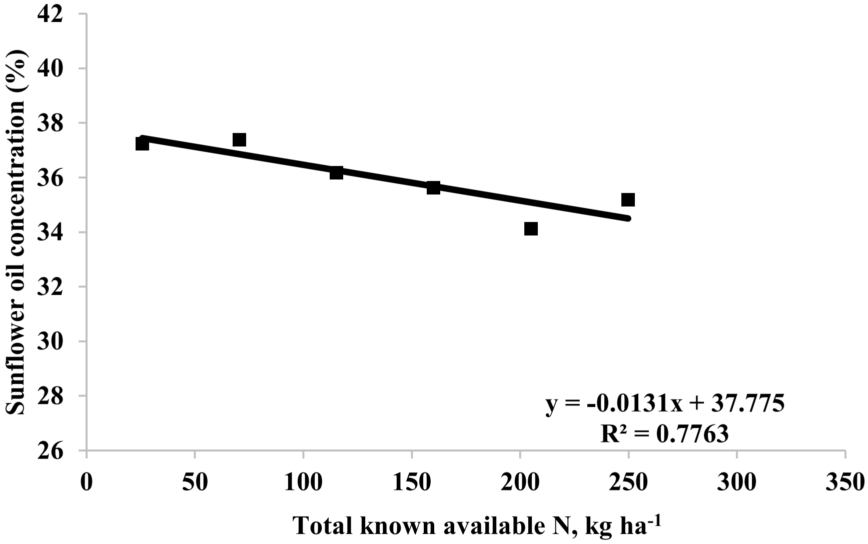

Figure 12. Relationship between total known available N and 2015 Valley City sunflower oil concentration.

Dickinson South 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 Dickinson South yield and oil data, adjusted for 10% moisture, are provided in Table 22 with associated p-values available in Table 23. Sunflower yield at Dickinson South in 2014 increased with increasing N rate. Highest sunflower yield was obtained from the 90 kg ha^{-1} N treatments and greater, of which the 90 and 180 kg ha^{-1} N treatments were not statistically different from the check N treatment. Oil concentration in 2014 decreased with increasing N rate. The addition of 45, 90, and 135 kg ha^{-1} of N treatments were not statistically different from the check. Oil concentration decreased with N rates of 180 and 225 kg ha^{-1}. In 2014 no significant effect of P application rate was found at Dickinson South for sunflower yield and oil concentration.

Table 22. ANOVA analysis of 2014 Dickinson South oilseed sunflower yield and quality. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1529c[†]	37.1ab	0	1836a	37.3a
45	1768bc	38.1a	33	1929a	37.3a
90	1834abc	38.2a	67	1827a	37.1a
135	1981ab	37.2ab	101	1767a	37.4a
180	1816abc	36.8b			
225	2120a	36.1b			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 23. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Dickinson South, 2014.

Source of variation	Yield	Oil concentration
N	0.0185	0.0038
P	0.6938	0.9151
N x P	0.9909	0.7569

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 Dickinson South sunflower with total known available N relationship to yield and oil concentration are presented in Figure 12 and Figure 13. The linear regression of Dickinson South yield and total known available N was significant with an r^2 of 0.75. The regression analysis of sunflower oil concentration with N rate for Dickinson South in 2014 was not significant.

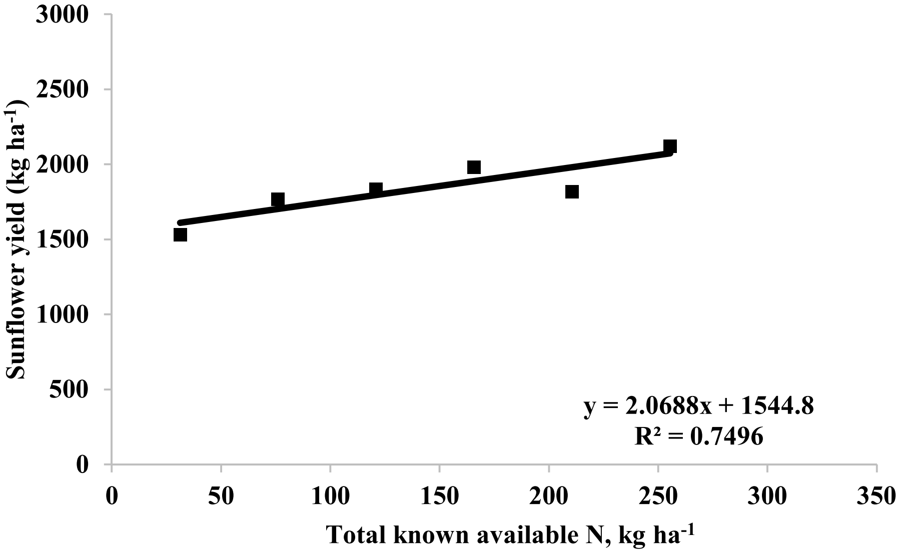

Figure 13. Relationship between total known available N and 2014 Dickinson South sunflower yield.

Hazelton 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 Hazelton yield and oil data, adjusted for 10% moisture, are provided in Table 24 with associated p-values available in Table 25. Sunflower yield increased with N rate in 2014 at Hazelton. Yield at 135, 180, and 225 kg N ha^{-1} rates were significantly greater than the check yield. Oil concentration increased with N rate to 90 and 135 kg ha^{-1} treatments and then decreased to statistically equal oil concentrations for

180 and 225 kg ha^{-1} N rates. No significant effect of P application was found at Hazelton in 2014. The soil test P level of 19 mg kg^{-1} would place the soil test P at a high availability level.

Table 24. ANOVA analysis of 2014 Hazelton oilseed sunflower yield and quality. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1643c[†]	37.4ab	0	1912a	37.3a
45	1856bc	37.4ab	33	1887a	37.4a
90	1797bc	37.7a	67	1932a	37.5a
135	2002ab	37.7a	101	1917a	37.2a
180	2010ab	37.0ab			
225	2164a	36.8b			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 25. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Hazelton, 2014.

Source of variation	Yield	Oil concentration
N	0.0002	0.1455
P	0.9646	0.8686
N x P	0.7047	0.8145

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 Hazelton sunflower yield is presented in Figure 13. Sunflower yield response to N at Hazelton was linear. The regression model for yield is highly significant with an r^2 of 0.90. The regression analysis of sunflower oil concentration with N rate was not significant.

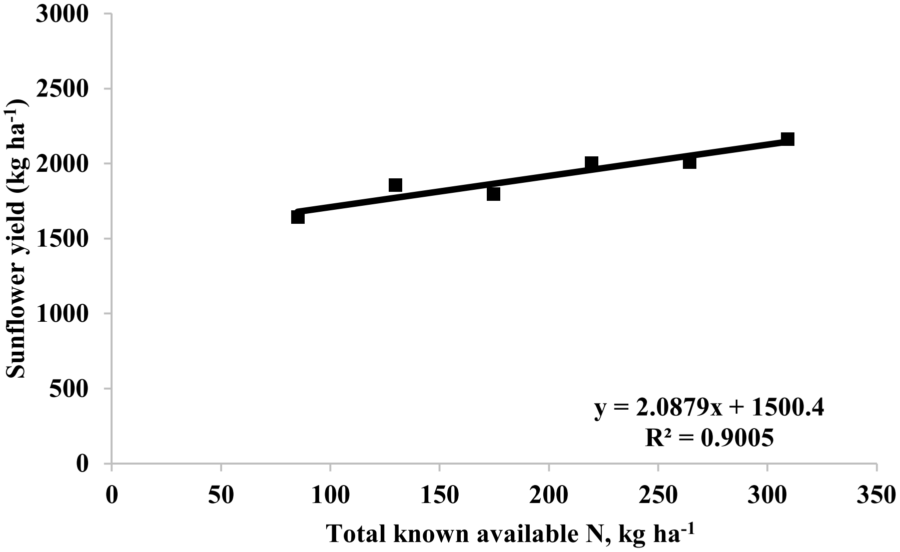

Figure 14. Relationship between total known available N and 2014 Hazelton sunflower yield.

Hazen 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 Hazen yield and oil data, adjusted for 10% moisture, are provided in Table 26 with associated p-values available in Table 27. Sunflower yield increased with the 45 kg ha^{-1} N rate from the check N treatment rate but did not increase further with additional N. There was 92 kg ha^{-1} of NO_3^- - N_{0-60} which may have contributed to the lack of additional response. The 45 kg ha^{-1} N rate provided the greatest oil concentration (39.1%) compared to lower oil concentrations at the 180 and 225 kg ha^{-1} N rates. No significant effect of P application rate was found on sunflower yield at Hazen in 2014. The P soil test at Hazen (Table 6) was 18 mg kg^{-1} which would be considered in the high range of available P. Oil concentration at Hazen in 2014 was only significantly affected by the 101 kg ha^{-1} P rate, which increased the oil concentration to 39.1%, but the increased oil would not have been an economic return to added P.

Table 26. ANOVA analysis of 2014 Hazen oilseed sunflower yield and quality. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1180b†	38.0abc	0	1492a	37.7b
45	1569a	39.1a	33	1521a	37.3b
90	1578a	38.4ab	67	1505a	37.5b
135	1556a	38.1abc	101	1589a	39.1a
180	1552a	37.0bc			
225	1739a	36.9c			

†Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 27. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Hazen, 2014.

Source of variation	Yield	Oil concentration
N	0.0044	0.0291
P	0.7852	0.0098
N x P	0.1210	0.3996

Regression Analysis – Yield and Oil Concentration

The r^2 values for the regression analysis for 2014 Hazen sunflower yield and oil concentration with total known available N were not significant.

Heil 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2014 Heil yield and oil data, adjusted for 10% moisture, are provided in Table 28 with associated p-values available in Table 29. Sunflower yield for Heil in 2014 increased with the 90 kg ha^{-1} N treatment, but additional N did not increase yield further. Oil concentration increased with N rate, with highest concentrations from N rates of 135, 180, and 225 kg ha^{-1}. The Heil location had NO_3^- - $N_{0\text{-}60}$ of 116 kg ha^{-1}, which may have contributed to lack of yield increase with greater N rate. The low oil concentration with the check plot is another indication that high initial soil N may have contributed to lack of yield response, but it is curious that oil concentration increased with N rates, when the expected outcome was the reverse. Studies that have recorded oil concentration increase with N rate are usually sites with low natural N availability (Mollashahi et al., 2013; Salih 2013; Oyinlola et al., 2013). There was no significant effect of P treatment rates on sunflower yield or oil concentration at Heil in 2014.

Table 28. ANOVA analysis of 2014 Heil oilseed sunflower yield and quality. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1822c[†]	36.7c	0	2144a	38.1a
45	2151bc	38.4ab	33	2310a	38.3a
90	2355ab	37.2bc	67	2345a	38.3a
135	2482ab	38.5ab	101	2333a	38.6a
180	2319ab	39.3a			
225	2619a	39.5a			

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 29. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Heil, 2014.

Source of variation	Yield	Oil concentration
N	0.0004	0.0034
P	0.4522	0.9084
N x P	0.6264	0.9725

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2014 Heil sunflower with total known available N relationship to yield and oil concentration are presented in Figure 14 and Figure 15. The increasing yield and oil concentrations result in two highly significant regression models for yield and oil concentration. For these models, the r^2 was 0.88 and 0.76 for yield and oil concentration, respectively. Yield increased until reaching a plateau at the 180 kg ha^{-1} N treatment rate, while oil concentration continued to increase beyond the 225 kg ha^{-1} N treatment rate.

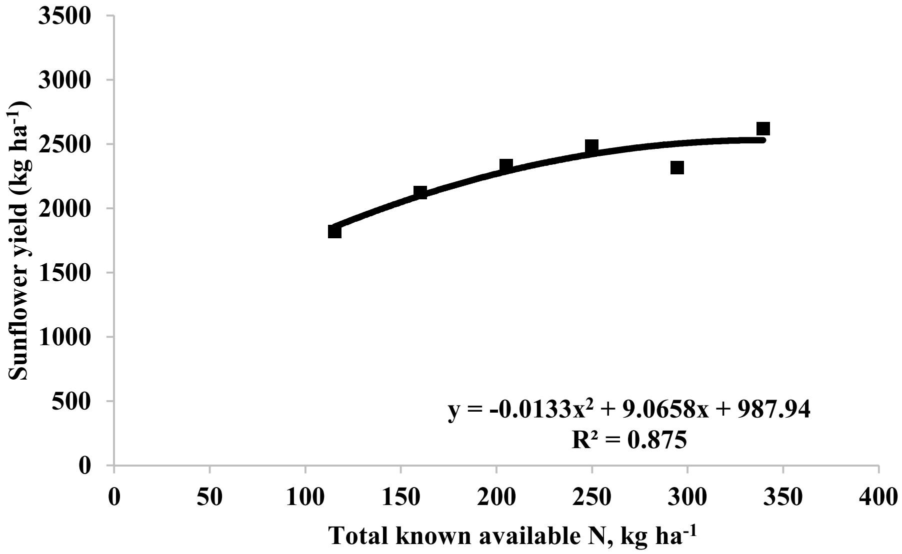

Figure 15. Relationship between total known available N and 2014 Heil sunflower yield.

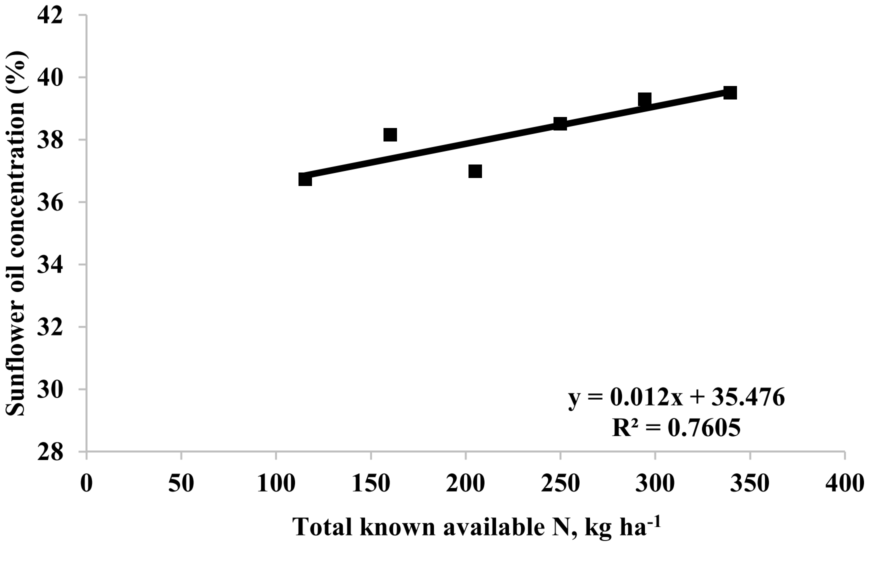

Figure 16. Relationship between total known available N and 2014 Heil sunflower oil concentration.

Amenia 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Amenia yield and oil data, adjusted for 10% moisture, are provided in Table 30 with associated p-values available in Table 31. Sunflower yield increased with addition of the 90 kg ha^{-1} N treatment rate in 2014, however, higher N rates did not result in higher yield. The effect of N rate on oil concentration for Amenia in 2015 is a decreasing trend from check N treatments to 225 kg ha^{-1} N rates. The highest oil concentration of 37.8% was obtained from the check N treatments, and all other N rate treatments were significantly lower. This site had not been seeded to a deep-rooted crop such as sugar beet (*Beta vulgaris* L.) or sunflower in decades. Therefore it is likely that there were high levels of NO_3^- - N present deeper than the study sampling depth of 60 cm. No effect of P on sunflower yield or oil concentration was observed in data from Amenia in 2015. The P soil test level was 28 mg kg^{-1} which is the highest among any site location in 2014 or 2015, and provided sufficient P for sunflower besides the P treatment rates.

Table 30. ANOVA analysis of 2015 Amenia oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1868b[†]	37.8a	0	2374a	35.9a
45	2100ab	36.5b	67	2238a	35.6a
90	2379a	35.8bc			
135	2535a	35.3c			
180	2536a	34.8cd			
225	2486a	33.8d			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 31. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Amenia, 2015.

Source of variation	Yield	Oil concentration
N	0.0460	<0.0001
P	0.2070	0.2033
N x P	0.9647	0.3970

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2015 Amenia sunflower with total known available N relationship to yield and oil concentration are presented in Figure 16 and Figure 17. Sunflower yield is maximized with a 247 kg ha^{-1} total known available N level. The quadratic regression of yield with total known available N was significant with an r^2 of 0.98. The decrease in oil concentration, peaking at the check N treatments and declining with all other N rates results in a significant regression model for normalized oil concentration with an r^2 of 0.98.

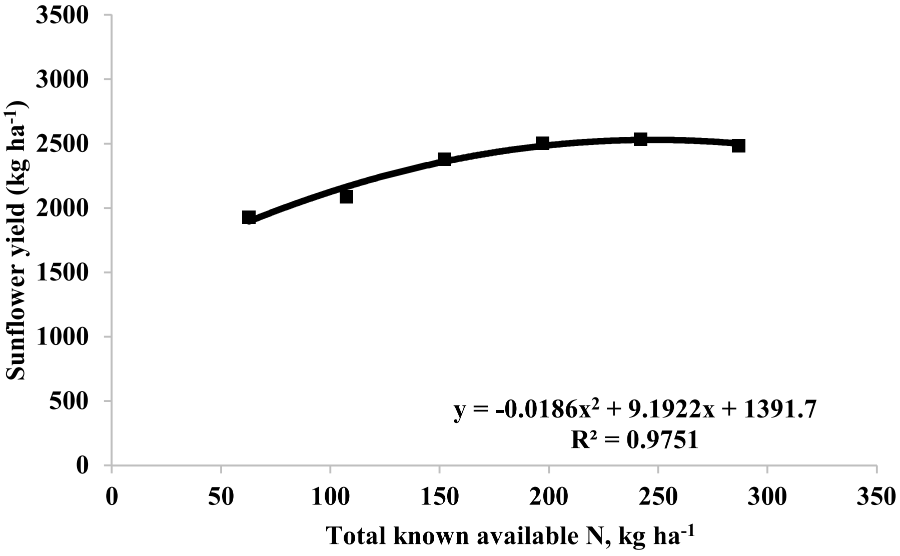

Figure 17. Relationship between total known available N and 2015 Amenia sunflower yield.

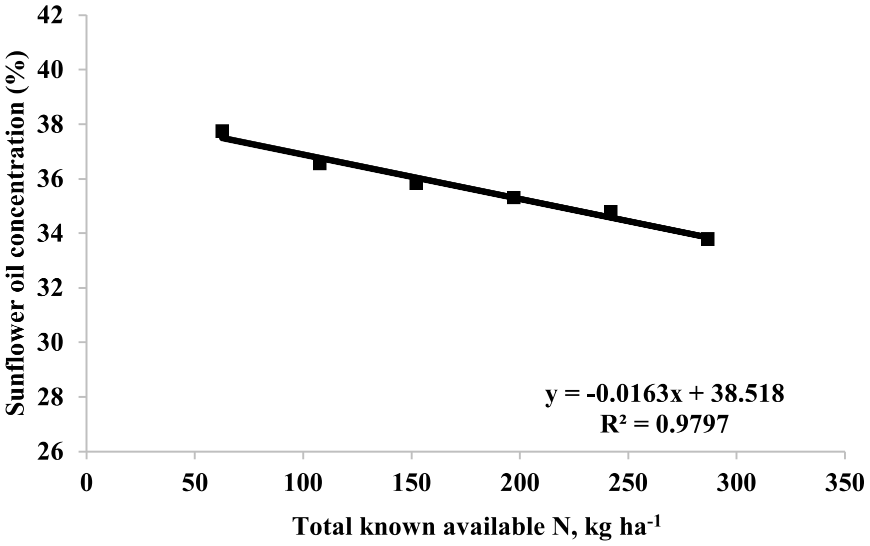

Figure 18. Relationship between total known available N and 2015 Amenia sunflower oil concentration.

Bottineau North 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Bottineau North yield and oil data, adjusted for 10% moisture, are provided in Table 32 with associated p-values available in Table 46. Bottineau North in 2015 experienced severe plant lodging as well as white mold. White mold disease in sunflower is caused by the pathogen *Sclerotinia sclerotiorum* (Lib.) *de Bary*. Environmental conditions of ample soil moisture and cool temperatures near Bottineau North in 2015 resulted in ideal conditions for *Sclerotinia* stem/head rot infection (Gulya et al., 1997), and significant infection occurred, especially in lodged sunflower plants. Yield losses of 1 to 20% due to white mold have been reported (Purdy, 1979; Gulya et al., 1986; Rashid, 1993). Sunflower yields in 2015 at Bottineau North did not increase with increasing N rate, except for the 135 kg ha^{-1} N rate yielding a significantly higher 2,647 kg ha^{-1} as compared to the 90 kg ha^{-1} yielding 2,261 kg ha^{-1} of sunflower. Oil concentration was reduced with increasing N rate at and above the 135 kg ha^{-1} N treatment rate.

Table 32. ANOVA analysis of 2015 Bottineau North oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	2538ab[†]	44.2a	0	2415a	43.4a
45	2592ab	43.6a	67	2601a	42.8b
90	2261b	43.4ab			
135	2647a	42.7bc			
180	2551ab	42.5c			
225	2458ab	42.2c			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 33. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Bottineau North, 2015.

Source of variation	Yield	Oil concentration
N	0.2800	0.0002
P	0.0636	0.0378
N x P	0.2789	0.1051

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2015 Bottineau North sunflower with total known available N relationship to oil concentration is presented in Figure 18. The check N treatment had the highest oil concentration, while oil concentration decreased with N rate. The linear regression of oil concentration with N rate was highly significant (r^2 of 0.97). The regression analysis of yield with N rate was not significant.

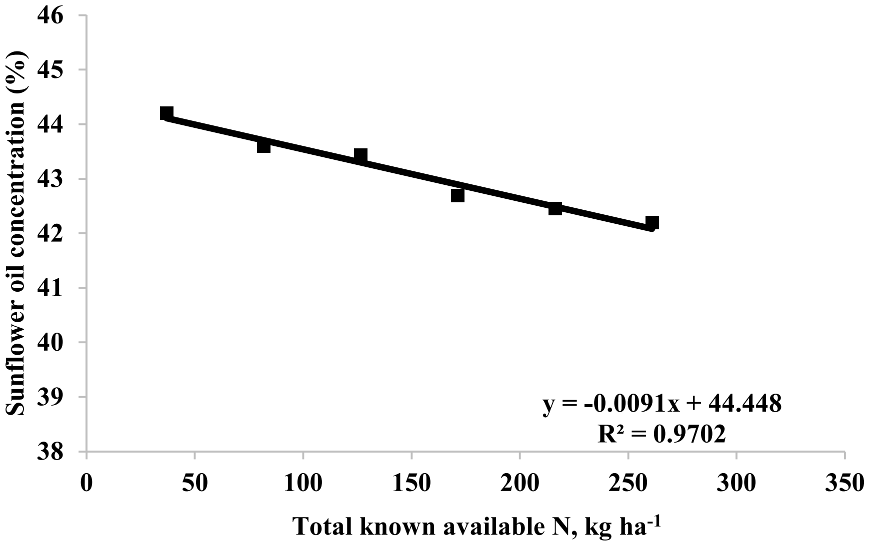

Figure 19. Relationship between total known available N and 2015 Bottineau North sunflower oil concentration.

Lodging Regression Analysis

Regression analysis for 2015 Bottineau North sunflower with total known available N relationship to sunflower percent lodging is shown in Figure 20. The linear regression was highly significant (r^2 = 0.91) for percent lodging and total known available N, and percent lodging increased with N rate. The average sunflower plants harvested per row was 34 at Bottineau North in 2015. The number of plants lodged for the 45, 90, 135, 180, and 225 kg N ha^{-1} treatments was 29, 25, 19, 19, 18, and 12, respectively.

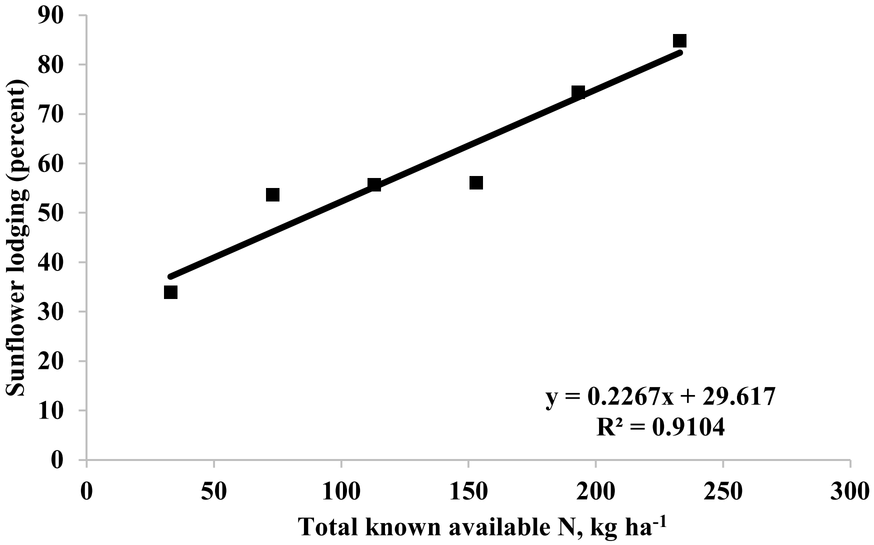

Figure 20. Relationship between total known available N and 2015 Bottineau North sunflower percent lodging.

Bottineau South

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Bottineau South yield and oil data, adjusted for 10% moisture, are provided in Table 34 with associated p-values available in Table 48. Yields for all N rate treatments were significantly greater than the yield for the check N rate, however, none of the yields for any of the N rates were significantly different. The long-term no-tillage location at Bottineau South had 4.9% organic matter (Table 7) and 47 kg ha^{-1} of NO_3^- - $N_{0\text{-}60}$, providing enough N to reduce the effects of N treatments. Oil concentration decreased with increasing N rate. Oil concentration reached a maximum average for the 45 kg ha^{-1} N treatment, and was significantly less for N rates of 135, 180, and 225 kg ha^{-1}. No significant effects from P rate treatments were found on sunflower yield or oil concentration at Bottineau South in 2015. Bottineau South in 2015 had similar lodging as Bottineau North, although not the severity of white mold (*Sclerotinia sclerotiorum (*Lib.) de Bary) incidence.

Downy mildew (*Plasmopara halstedii* (Farl.) Berl. & de Toni) also randomly infested this location, decreasing yields of systemically-infected plants.

Table 34. ANOVA analysis of 2015 Bottineau South oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1506b[†]	43.7a	0	2168a	42.8a
45	2100a	44.3a	67	2093a	42.9a
90	2359a	43.3ab			
135	2173a	42.3bc			
180	2413a	42.5b			
225	2231a	41.1c			

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 35. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Bottineau South, 2015.

Source of variation	Yield	Oil concentration
N	0.0003	<0.0001
P	0.4852	0.6924
N x P	0.8899	0.8901

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2015 Bottineau South sunflower with total known available N relationship to yield and oil concentration are presented in Figure 19 and Figure 20. The decrease in attained yield with application rate of 135 kg ha^{-1} of N results in a nonsignificant model for yield of 2015 Bottineau South. The random occurrence of both lodging and downy mildew within the plot area contributed greater to variation in yield then the N treatment rates. Oil concentration is found to decrease with increasing N rate, and is a highly significant regression model ($r^2 = 0.83$).

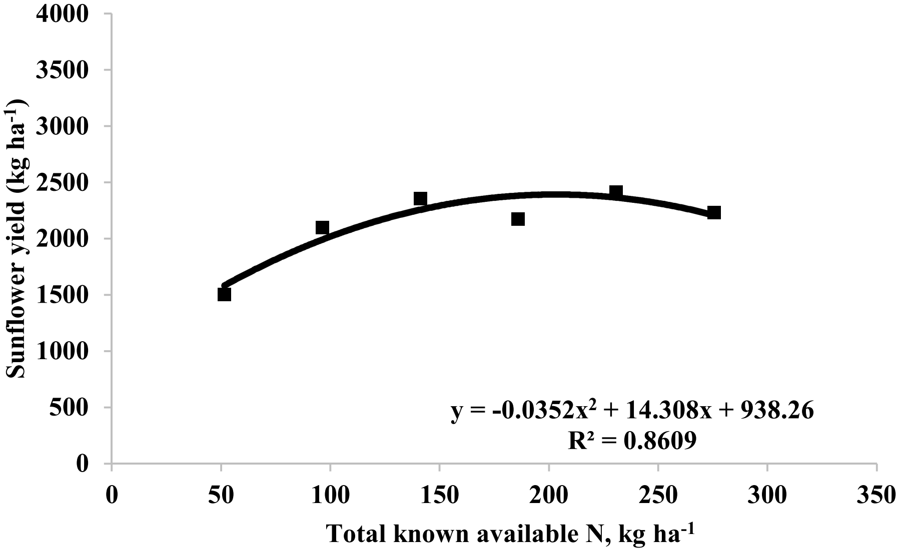

Figure 21. Relationship between total known available N and 2015 Bottineau South sunflower yield.

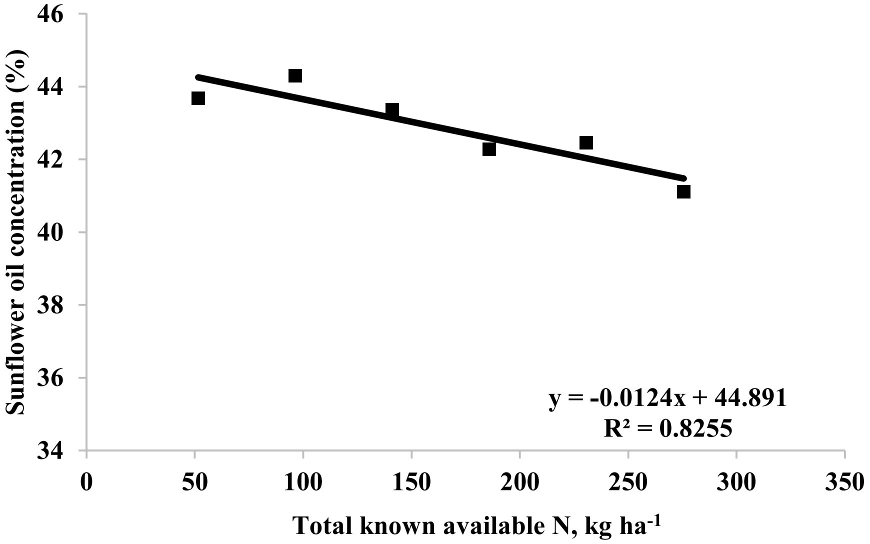

Figure 22. Relationship between total known available N and 2015 Bottineau South sunflower oil concentration.

Regression Analysis – Lodging

Bottineau North 2015 regression analysis for sunflower is presented in Figure 23. The relationship of total known available N and sunflower percent lodging was linear, highly significant (r^2=0.97), and sunflower percent lodging increased with N rate. The average sunflower plants harvested per row was 30 at Bottineau South in 2015. The number of plants lodged for the 45, 90, 135, 180, and 225 kg N ha^{-1} treatments was 22, 18, 17, 11, eight, and three, respectively.

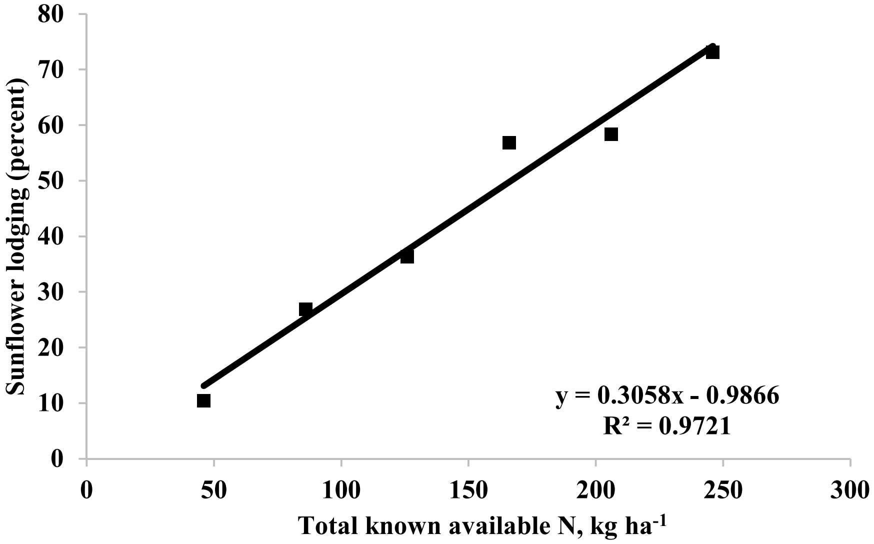

Figure 23. Relationship between total known available N and 2015 Bottineau South sunflower percent lodging.

Coleharbor 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Coleharbor yield and oil data, adjusted for 10% moisture, are provided in Table 36 with associated p-values in available in Table 37. There was no significant response of sunflower yield or oil concentration to N fertilizer rate or P fertilizer rate at Coleharbor in 2015. Lacking response to N could be due to 101 kg ha^{-1} of NO_3^- - $N_{0\text{-}60}$ and 4.1% organic matter (Table 7) contributing to the N supply for the sunflowers or the losses of sunflower yield due to lodging. There was also no response of yield or oil concentration to P rate in 2015 at Coleharbor. No significant soil test P levels were present (Table 7), although selected effects from the above influences on the response to N may have also contributed to the no response to P as well.

Table 36. ANOVA analysis of 2015 Coleharbor oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	1896b[†]	44.3a	0	1915a	44.1a
45	1950ab	44.3a	67	2022a	44.1a
90	1882a	44.3a			
135	1930ab	44.2ab			
180	2010ab	44.0ab			
225	2142a	43.5b			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 37. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Coleharbor, 2015.

Source of variation	Yield	Oil concentration
N	0.2946	0.1666
P	0.1330	0.8571
N x P	0.6802	0.1959

Regression Analysis – Yield and Oil Concentration

The r^2 values for the regression analysis for 2015 Coleharbor sunflower yield and oil concentration with total known available N were not significant.

Elgin 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Elgin yield and oil data, adjusted for 10% moisture, are provided in Table 38 with associated p-values available in Table 39. There was no significant response of sunflower yield or oil concentration to N fertilizer rate or P fertilizer rate at Elgin in 2015. The NO_3^- - $N_{0\text{-}60}$ level was relatively high (94 kg ha^{-1}) as was the organic matter (5.6%) (Table 7).

Table 38. ANOVA analysis of 2015 Elgin oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	2819b[†]	43.6a	0	3138a	43.0a
45	3109ab	42.8a	67	3174a	43.1a
90	3390a	42.6a			
135	3218a	43.2a			
180	3170ab	43.1a			
225	3228a	42.9a			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 39. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Elgin, 2015.

Source of variation	Yield	Oil concentration
N	0.0837	0.6742
P	0.7308	0.7737
N x P	0.8932	0.3382

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2015 Elgin sunflower yield and oil concentration with total known available N was not significant.

Linton 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield and Quality

Results of ANOVA analysis for N rate and P rate of 2015 Linton yield and oil data, adjusted for 10% moisture, are provided in Table 40 with associated p-values available in Table 41. Sunflower yield did not respond to N or P rate in 2015 at Linton. Oil concentration was highest for the check N rate and 45 kg ha^{-1} N rate and decreased with the addition of higher N rate treatments (90, 135, 180, and 225 kg ha^{-1}). No effect was found of P rate on oil concentration at Linton in 2015.

Table 40. ANOVA analysis of 2015 Linton oilseed sunflower yield and quality. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	Oil concentration	P rate	Yield	Oil concentration
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}	kg ha^{-1}	%
0	2242a[†]	37.7a	0	2262a	36.3a
45	2390a	37.1a	67	2317a	36.1a
90	2243a	36.1b			
135	2280a	35.4bc			
180	2291a	35.1c			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 41. P-values for N main effect, P main effect, and N x P interaction for sunflower yield and oil concentration at Linton, 2015.

Source of variation	Yield	Oil concentration
N	0.8875	<0.0001
P	0.5927	0.5924
N x P	0.1005	0.6798

Regression Analysis – Yield and Oil Concentration

Regression analysis for 2015 Linton sunflower with total known available N relationship to oil concentration is presented in Figure 21. The regression model is highly significant with an r^2 of 0.98. Oil concentration was highest for the check N treatment and then decreased with additional N rates. The r^2 for 2015 Linton sunflower yield was not significant.

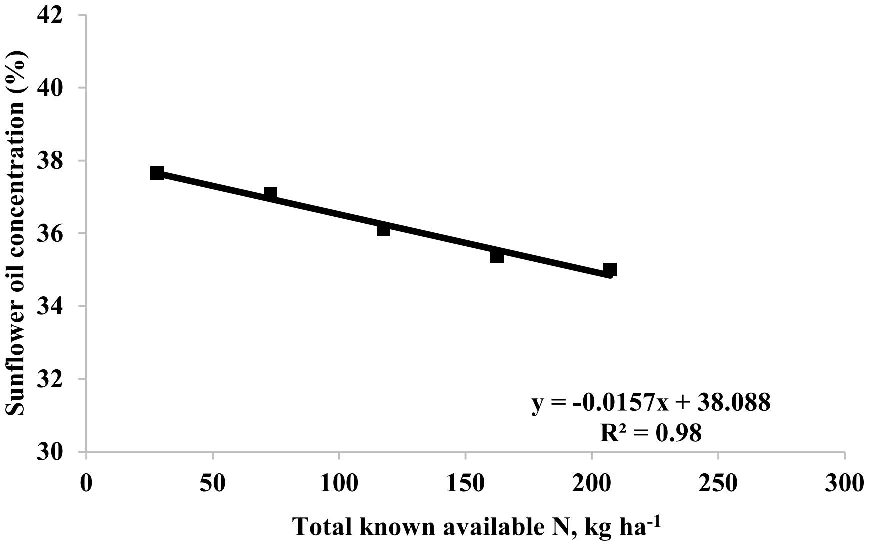

Figure 24. Relationship between total known available N and 2015 Linton sunflower oil concentration.

RESULTS AND DISCUSSION FOR CONFECTIONARY SUNFLOWER

Walcott 2014 and 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield

Results of ANOVA analysis for N rate and P rate of 2014 and 2015 Walcott yield data, adjusted for 10% moisture, are provided in Table 42 with associated p-values available in Table 43. No significant effect of N or P application rate was found on yield at Walcott in 2014. The soil test results for NO_3^- - N are only to the 30 cm depth, due to frozen soil, and indicate 68 kg ha^{-1} of NO_3^- - N. The NO_3^- - N between 30 and 60 cm may have contributed to the N supply for sunflower in 2014. Location of the plot area in 2014 also resulted in bird damage of sunflower heads influencing yields throughout the plot area. In 2015, yields increased with N application rate and were not affected by P application rate.

Table 42. ANOVA analysis of 2014 and 2015 Walcott confectionary sunflower yield. Nitrogen rate results are averaged across four and two phosphorus rates in 2014 and 2015, respectively, and phosphorus rate results are averaged across six nitrogen rates in 2014 and 2015.

	2014	2015		2014	2015
N rate	**Yield**	**Yield**	**P rate**	**Yield**	**Yield**
kg ha^{-1}	**kg ha^{-1}**	**kg ha^{-1}**	**kg ha^{-1}**	**kg ha^{-1}**	**kg ha^{-1}**
0	2411a[†]	2897d	0	2298a	3399a
45	2392a	3231cd	33	2343a	
90	2565a	3410bcd	67	2349a	3714a
135	2339a	3640abc	101	2349a	
180	2282a	4128a			
225	2319a	4034ab			

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 43. P-values for N main effect, P main effect, and N x P interaction for sunflower yield at Walcott, 2014 and 2015.

Source of variation	2014	2015
N	0.8741	0.0075
P	0.9632	0.1201
N x P	0.4885	0.8643

Regression Analysis – Yield

Regression analysis for 2015 Walcott sunflower with total known available N relationship to yield is presented in Figure 28. The regression model is linear and is highly significant with an r^2 of 0.94. The r^2 for 2014 Walcott sunflower with total known available N relationship to yield was not significant.

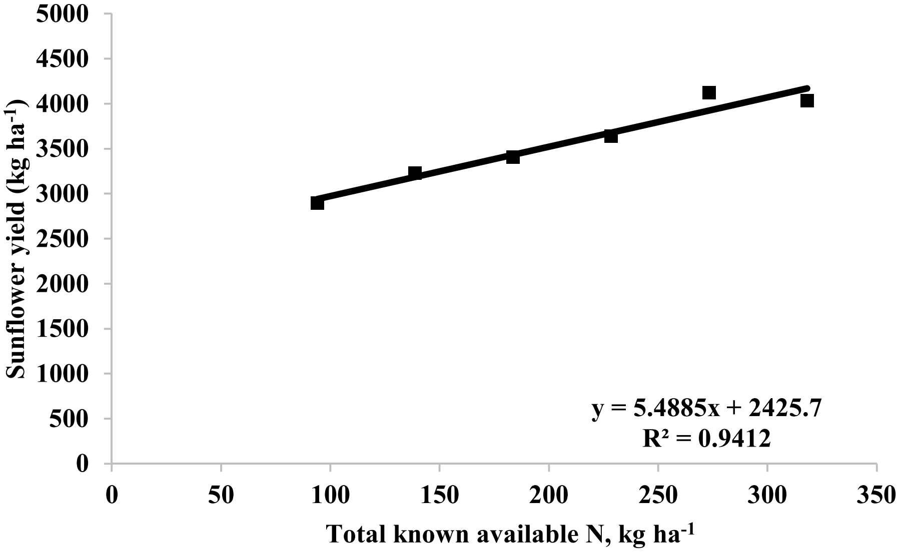

Figure 25. Relationship between total known available N and 2015 Walcott sunflower yield.

Cummings 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield

Results of ANOVA analysis for N rate and P rate of 2014 Cummings yield data, adjusted for 10% moisture, are provided in Table 44 with associated p-values available in Table 45. No significant yield response to N or P fertilizer application rate was found in 2014 at Cummings.

The site had a very large random infestation of downy mildew (*Plasmopara halstedii* (Farl.) Berl. & de Toni) which negatively impacted yields, and influenced yield response. Sunflower plants which grew next to downy mildew infected plants compensated for the infected plant's decreased size and growth with larger heads than would normally be expected and greater yields from these individual plants as well. Due to the infestation of downy mildew, there was significant loss of plant stand at the 2014 Cummings site location. Decreased yields of downy mildew infested plants as well as decreased plant stands reduced yields significantly. Also, the NO_3^- - $N_{0\text{-}60}$ at Cummings in 2014 was the highest among all site-years (Table 6) at 205 kg ha^{-1}.

Table 44. ANOVA analysis of 2014 Cummings confectionary sunflower yield. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate kg ha^{-1}	Yield kg ha^{-1}	P rate kg ha^{-1}	Yield kg ha^{-1}
0	1635ab†	0	1693a
45	1814ab	33	1714a
90	1903a	67	1776a
135	1712ab	101	1795a
180	1531b		
225	1835ab		

†Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 45. P-values for N main effect, P main effect, and N x P interaction for sunflower yield at Cummings, 2014.

Source of variation	Yield
N	0.2819
P	0.8536
N x P	0.8712

Regression Analysis – Yield

The r^2 for 2014 Cummings sunflower yield relationship with total known available N was not significant.

Dickinson North 2014

Analysis of the Effect of N and P Fertilizer Rate on Yield

Results of ANOVA analysis for N rate and P rate of 2014 Dickinson North yield data, adjusted for 10% moisture, are provided in Table 46 with associated p-values available in Table 47. Sunflower yield increased with addition of 45, 90, and 135 kg ha^{-1} N rates compared to the check N treatment, and were not significantly different than the check N treatment for N rates of 180 and 225 kg ha^{-1}. There was a very high NO_3^- - N_{0-60} level (149 kg ha^{-1}), shown in Table 6, which reduced the effect of N rates on yield. The P soil test results also indicate a very high level of 32 mg kg^{-1}, which indicates that sunflower would not respond to an application of P, which it did not in 2014.

Table 46. ANOVA analysis of 2014 Dickinson North confectionary sunflower yield. Nitrogen rate results are averaged across four phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	P rate	Yield
kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
0	1716bc†	0	1900a
45	1999a	33	1898a
90	2015a	67	1835a
135	2036a	101	1973a
180	1685c		
225	1955ab		

†Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 47. P-values for N main effect, P main effect, and N x P interaction for sunflower yield at Dickinson North, 2014.

Source of variation	Yield
N	0.0224
P	0.6539
N x P	0.3777

Regression Analysis – Yield

Regression analysis for 2014 Dickinson North sunflower with total known available N relationship to yield was not significant.

Dickinson 2015

Analysis of the Effect of N and P Fertilizer Rate on Yield

Results of ANOVA analysis for N rate and P rate of 2015 Dickinson yield data, adjusted for 10% moisture, are provided in Table 48 with associated p-values available in Table 49. There was no effect on sunflower yield of N or P fertilizer rate in 2015 at Dickinson. The NO_3^- - $N_{0\text{-}60}$ of 94 kg ha^{-1} (Table 4) as well as influence from sunflower rust (caused by the fungal pathogen *Puccinia helianthi*) may have reduced the response to N rate. Results of ANOVA analysis for N rate and 2015 Dickinson sunflower rust severity ratings are provided in Table 50. Sunflower rust infection can decrease head size, seed size, oil content, and yield (Chattopadhyay et al., 2016), with the greatest impact on confectionary sunflower being reduced seed size (Siddiqui, 1980). Yield losses caused by sunflower rust typically range from 25 to 50% (Chattopadhyay et al., 2016) but can be much higher in localized hot spots (Friskop et al., 2011).

Table 48. ANOVA analysis of 2015 Dickinson confectionary sunflower yield. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	P rate	Yield
kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
0	3328a†	0	3537a
45	3574a	67	3447a
90	3509a		
135	3600a		
180	3359a		
225	3581a		

†Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table 49. P-values for N main effect, P main effect, and N x P interaction for sunflower yield at Dickinson, 2015.

Source of variation	**Yield**
N	0.9081
P	0.6177
N x P	0.5365

Table 50. ANOVA analysis of 2015 Dickinson sunflower rust severity ratings.

N rate kg ha^{-1}	Sunflower rust rating
0	0.65b
45	1.51ab
90	2.25a
135	1.53ab
180	1.25ab
225	1.63ab

Regression Analysis – Yield

Regression analysis of 2015 Dickinson sunflower yield relationship with total known available N was not significant.

RESULTS AND DISCUSSION FOR SITE-YEARS CATEGORIZATION

Introduction

The initial regression analysis of oilseed and confectionary sunflower yield and oil concentration was performed on individual site-years. Recalibrating N and P for sunflower can be useful for responses to be applicable in a greater area than the response to N and P for only individual site-years. On the basis of applying the response of sunflower to N and P to North Dakota, site-years were grouped together. Multiple regression analysis was conducted on the site-years with the categories of region (western or eastern North Dakota), tillage (long-term no-tillage or conventional tillage), and seed type (oilseed or confectionary). The results strongly indicated that yield responses to N were different between eastern no-tillage and eastern conventional tillage sites and oilseed and confection sunflower in the western or eastern North Dakota region. The sites were therefore categorized into eastern no-tillage oilseed, eastern conventional tillage oilseed, eastern conventional tillage confectionary, western no-tillage oilseed, and western no-tillage confectionary sunflower (Table 51). Site-years that were included in the analysis were those that did not have any greater influences on yield than either the N rate treatments or the natural supply of N from the soil. Categorization of sunflower site-years was performed after Franzen (2011) and Franzen (2014).

Regional categorization of site-years is the result of climate and soil differences between eastern North Dakota and western North Dakota. Eastern North Dakota receives greater annual precipitation, and as a result is generally more humid than western North Dakota. In 2015, rainfall total between March and October in east-central North Dakota was approximately 450 mm compared to a rainfall total of 280 mm in west-central and western North Dakota (NDAWN, 2015). Greater rainfall can contribute to higher sunflower yields, but it can also result in greater early-season N loss.

Table 51. Site categorization for multiple regression analysis, 2014 and 2015.

Year	Site	Category
2014	Amidon	Western no-tillage oilseed
	Belfield	Western no-tillage oilseed
	Dickinson South	Western no-tillage oilseed
	Hazelton	Western no-tillage oilseed
	Hazen	Western no-tillage oilseed
	Heil	Western no-tillage oilseed
	Valley City	Eastern no-tillage oilseed
	Walcott	Eastern conventional tillage confectionary
2015	Amenia	Eastern conventional tillage oilseed
	Amidon	Western no-tillage oilseed
	Beach	Western no-tillage oilseed
	Bottineau North	Eastern no-tillage oilseed
	Bottineau South	Eastern no-tillage oilseed
	Coleharbor	Eastern no-tillage oilseed
	Elgin	Western no-tillage oilseed
	Valley City	Eastern no-tillage oilseed
	Walcott	Eastern conventional tillage confectionary

Eastern North Dakota

No-Tillage Oilseed Sunflower

No-tillage oilseed sunflower regression analysis relationship of total known available N and normalized sunflower yield is presented in Figure 26. The quadratic curve is a gradually increasing curve with a peak yield at 237 kg ha^{-1} of total known available N and a significant regression model (r^2=0.36). In no-till, N is typically used more efficiently by microorganisms partly because of increased microbial population and activity (Staley, 1999) as well as microbial biomass (Balota et al., 2003; Kandeler et al., 1999) in conservation tillage systems. This can contribute to decreased yield gains with addition of N at higher rates, as shown between 100 and 200 kg ha^{-1} of total known available N in Figure 23.

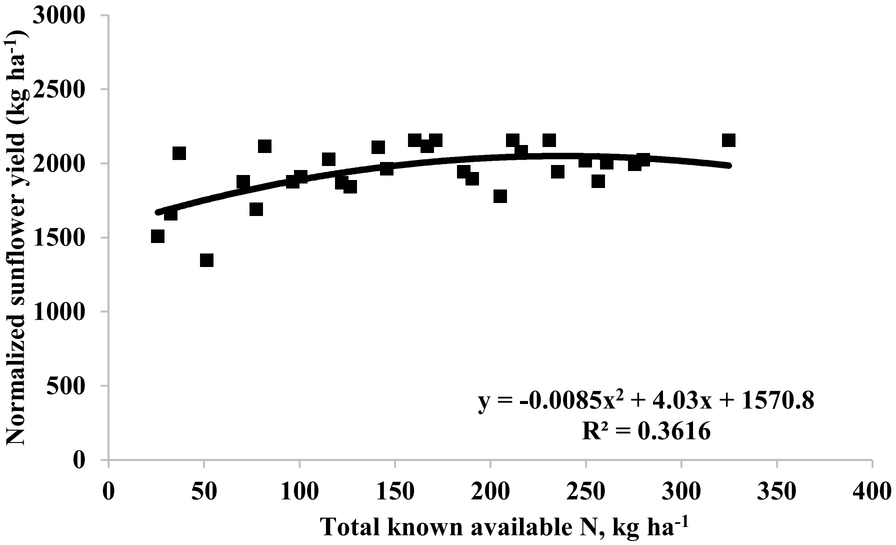

Figure 26. Relationship between total known available N and 2014 and 2015 eastern North Dakota no-tillage oilseed sunflower normalized yield.

Conventional Tillage Oilseed Sunflower

Eastern North Dakota conventional tillage oilseed sunflower regression analysis of total known available N and normalized sunflower yield is presented in Figure 27. Only one site-year (Amenia, 2015) is included in the analysis of conventional till oilseed sunflower in Eastern North Dakota. The quadratic regression for normalized yields at this location, Amenia 2015, has a peak yield at 248 kg ha^{-1} of total known available N and is highly significant, with an r^2 of 0.98. This conventional tillage oilseed site-year yielded higher than no-tillage oilseed site-years in eastern North Dakota and is shown to respond to application of N with greater incremental yield gains. This could be the result of early season denitrification loss of N due to high May and June rainfall on the high clay soil at this site compared to more efficient use of N in the eastern no-tillage fields (Figure 27).

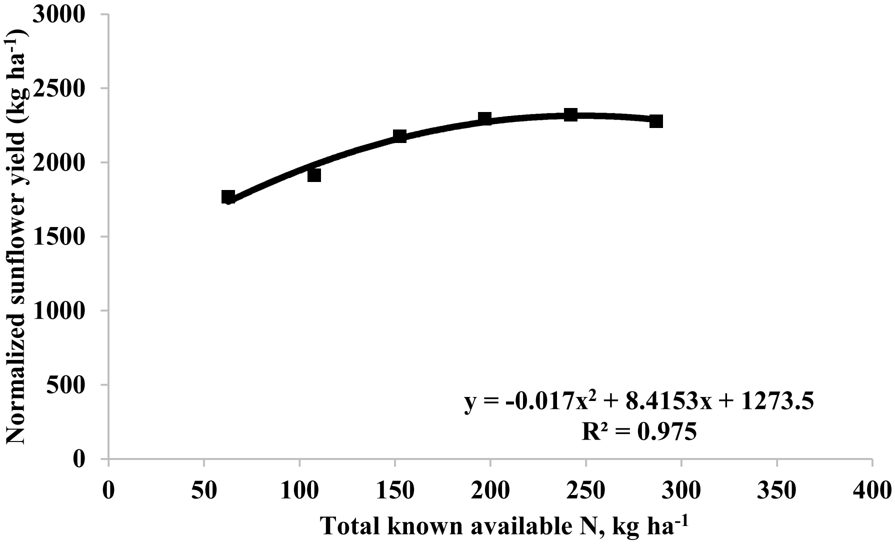

Figure 27. Relationship between total known available N and 2015 eastern North Dakota conventional tillage oilseed sunflower normalized yield.

Conventional Tillage Confectionary Sunflower

Eastern North Dakota conventional tillage confectionary sunflower regression analysis was not significant. Although two site-years in 2014 and 2015 at Walcott were included in the analysis, the yields were very different at low N rates. The NO_3^- - N in 2014 was only tested to the 30 cm depth, and, given the very high yields obtained at low N rates in this year, it is very likely that significant NO_3^- - N was present below 30 cm. A third location, at Cummings in 2014, was not included in the analysis due to a very high random incidence of downy mildew.

Western North Dakota

No-Tillage Oilseed Sunflower

Western North Dakota no-tillage oilseed sunflower regression analysis relationship of total known available N and normalized sunflower yield is presented in Figure 28. The western no-tillage oilseed site-years responded to N, although the response curve is different than that of the conventional tillage eastern North Dakota sites. The maximum N for the response is greater for the no-tillage than the eastern conventional tillage, and the response curve for the western no-tillage sites tends to plateau instead of curving downward. The quadratic model of the regression analysis of normalized yield with total known available N for western no-tillage sites is highly significant with an r^2 of 0.60. The quadratic curve has a maximum yield at 300 kg ha^{-1} of total known available N, slightly greater than that of the eastern no-tillage oilseed site-years.

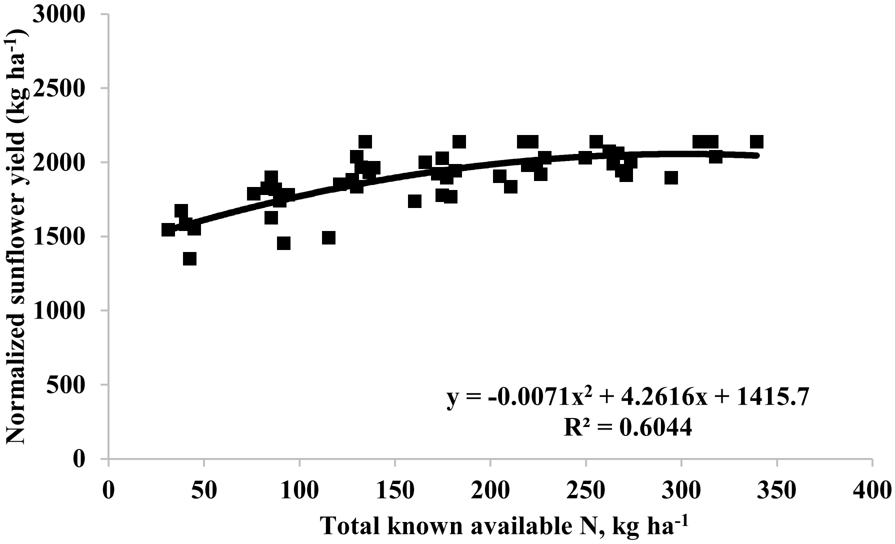

Figure 28. Relationship between total known available N and 2014 and 2015 western North Dakota no-tillage oilseed sunflower normalized yield.

No-Tillage Confectionary Sunflower

In 2014 and 2015, there were only two site-years classified as western North Dakota no-tillage confectionary sunflower. These site-years exhibit increased yield with N rate, however, the regression analysis relationship of total known available N and normalized yield was not significant.

CONCLUSIONS

The relationships between sunflower yield and sunflower oil concentration with N and P observed in this study indicate that current recommendations of N and P for sunflower in the northern Great Plains do not accurately reflect N and P uptake and its association with sunflower yield and oil concentration. These data represent modern N and P recommendations including updated soil test calibrations determining critical levels and dictating N and P fertilizer rates. Results from this study are indicative of modern sunflower responses to N and P fertilizer.

Oilseed sunflower exhibited prominent responses for yield and oil concentration to N fertilizer rate. Highly significant regression models for yield (quadratic polynomial models) and oil concentration (linear models) are frequently represented in the dataset. Sunflower yield generally increased with N rate until reaching the critical level, which conforms to the most relevant existing research in the northern Great Plains (Robinson, 1985; Zubriski et al., 1979; Cheng and Zubriski, 1978; Zubriski and Zimmerman, 1974; Robinson, 1973a; Robinson 1973b) and also the studies of Nasim et al., (2012), Oyinlola et al., (2010), and Zubillaga et al., (2002). Site-years for oilseed sunflower yields that were not responsive to the N treatments were either affected by high organic matter and/or $NO_3^- - N_{0\text{-}60}$, or weather conditions. Decreasing oil concentration with increasing N rate was found, which is in agreement with early northern Great Plains sunflower research (Robinson, 1985; Zubriski et al., 1979; Zubriski and Zimmerman, 1974) as well as recent work (Ozer et al., 2004; Zubillaga et al., 2002; Scheiner et al., 2002).

When oilseed site-years for eastern and western North Dakota are combined, highly significant relationships between total known available N and sunflower yield are found (Figure x and y) however, sunflower oil concentration relationship to total known available N is not significant (not shown). This is due to the decreasing linear trend at individual site-years specific for certain oil concentration averages, and the range of these averages, when combined, is not fit for regression analysis. Sunflower oil concentration decreased on average 2.0 to 2.5% from the check N treatments to high N treatments (135, 180, and 225 kg N ha^{-1}) across all responding site-years.

Confectionary sunflower site-years in 2014 and 2015 did not consistently respond to N fertilizer rates. Only one response was found among five site-years, Walcott 2015, which yield increased with increasing N. Influences at over half of the confectionary sunflower site-years in this particular study warrant a larger dataset in determining eastern or western North Dakota confectionary sunflower response to N. Reduction of the high NO_3^- - N_{0-60} and increased disease infection which limited this dataset would provide for modern recommendation responses better. Combining confectionary sunflower site-years results in a non-significant regression model for eastern North Dakota, furthering the idea that more responsive site-years should be added to the dataset in order to formulate the N recommendation.

The response of sunflower yield and sunflower oil concentration to P treatments in this study was almost non-existent. No regression models for P were presented because of the minimal response (2014, two site-year; 2015, one site-year) and lack of significant models. In these non-fallow rotation site-years in 2014 and 2015, sunflower root infection of VAM likely supplied sunflower P needs. The degree of mycorrhizal infection in sunflower is inversely related with soil P level (Connor and Hall, 1997) which helps to explain the low (< 7 mg kg^{-1}, Olsen test) and very low (< 3 mg kg^{-1}, Olsen test) P testing site-years not responding to the P treatments, these results are similar to Hibberd et al., (1991). Vesicular arbuscular mycorrhizae infection of sunflower roots results in sunflower not requiring any additionally supplied P.

Overall, the quadratic polynomial models were the best-predicting of sunflower yield response to total known available N, and by including this curvilinear relationship, shown by almost every individual site-year, N fertilizer recommendations will be able to improve sufficient application of N while decreasing potential for over- or under-application of N. Also, including oil concentration linear decrease with N fertilizer application rates increasing will protect sunflower quality. Not including P fertilizers in sunflower production was shown to not effect yield or oil concentration of sunflower in these studies. Incorporating the documented responses of eastern and western North Dakota oilseed and confectionary dataset responses into fertilizer recommendations will ensure a greater potential for the most efficient fertilizer application of N and P.

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APPENDIX

Table A1. Coefficients of variation (CV) for 2014 and 2015 North Dakota site-years yield and oil concentration results.

Year	Site	Yield CV	Oil concentration CV
		%	%
2014	Amidon	26.5	4.38
	Beach	17.1	4.03
	Belfield	15.4	3.00
	Cummings	26.3	NA[§]
	Dickinson North	19.8	NA
	Dickinson South	25.4	4.51
	Hazelton	16.0	3.03
	Hazen	23.7	5.34
	Heil	21.4	5.86
	Valley City	20.5	3.92
	Walcott	16.7	NA
2015	Amenia	19.6	3.28
	Amidon	20.0	4.54
	Beach	12.2	2.61
	Belfield	20.5	3.23
	Bottineau North	13.4	1.96
	Bottineau South	17.2	2.75
	Coleharbor	12.2	1.47
	Dickinson	17.6	NA
	Elgin	11.6	2.77
	Linton	14.1	2.42
	Valley City	19.8	4.76
	Walcott	19.2	NA

[§] Not applicable.

Table A2. Nitrogen rate ANOVA analysis of 2014 and 2015 New Underwood, South Dakota oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015
N rate	**Yield**	**Oil concentration**	**Yield**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**
0	1460a	37.2b	1198a
45	1423a	36.3a	1453a
90	1509a	36.1a	1402a
135	1443a	36.0a	1414a
180	1351a	35.8a	1472a
225	1421a	35.7a	1463a

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A3. Phosphorus rate ANOVA analysis of 2014 and 2015 New Underwood, South Dakota oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015
P rate	**Yield**	**Oil concentration**	**Yield**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**
0	1367a	35.9a	1312a
33	1435a	36.1a	
67	1438a	36.3a	1489a
101	1499a	36.4a	

[†]Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A4. Nitrogen rate ANOVA analysis of 2014 and 2015 Onida, South Dakota oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015
N rate	**Yield**	**Oil concentration**	**Yield**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**
0	1215a	37.9ab	1872ag
45	1288ab	37.5ab	1820ab
90	1295ab	38.6ab	1747a
135	1568b	39.1b	2136b
180	1459ab	36.9a	1910ab
225	1527b	37.5ab	1990ab

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A5. Phosphorus rate ANOVA analysis of 2014 and 2015 Onida, South Dakota oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015
P rate	**Yield**	**Oil concentration**	**Yield**
kg ha^{-1}	**kg ha^{-1}**	**%**	**kg ha^{-1}**
0	1345a	39.3a	1923a
33	1354a	37.3a	
67	1389a	37.9a	1914a
101	1482a	38.2a	

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A6. Nitrogen rate ANOVA analysis of 2014 and 2015 Pierre, South Dakota oilseed sunflower yield and quality averaged across four phosphorus rates in 2014 and two phosphorus rates in 2015.

	2014		2015
N rate	Yield	Oil concentration	Yield
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}
0	1727ab	42.6bc	1642a
45	2418b	42.6bc	1524a
90	1784ab	42.8c	1483a
135	2342ab	41.9ab	1556a
180	2352ab	42.2abc	1618a
225	1430a	41.7a	1577a

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A7. Phosphorus rate ANOVA analysis of 2014 and 2015 Pierre, South Dakota oilseed sunflower yield and quality averaged across six nitrogen rates.

	2014		2015
P rate	Yield	Oil concentration	Yield
kg ha^{-1}	kg ha^{-1}	%	kg ha^{-1}
0	1902a	42.2a	1609a
33	1991a	42.3a	
67	2399a	42.2a	1457a
101	1743a	42.5a	

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A8. Nitrogen rate ANOVA analysis of 2015 Caputa, South Dakota oilseed sunflower yield. Nitrogen rate results are averaged across two phosphorus rates and phosphorus rate results are averaged across six nitrogen rates.

N rate	Yield	P rate	Yield
kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
0	1215ab	0	1160a
45	1089ab	67	1121a
90	1356b		
135	1155ab		
180	973a		
225	1057ab		

[†] Means with the same letter within the same column are not significantly different at $P < 0.05$ based on the LSD test.

Table A9. South Dakota 2014 and 2015 selected location, soil, and sunflower crop information.

Year	Location	Tillage[†]	Previous crop	Seed type	Cultivar	Oil type	Row width
							— cm —
2014	Onida	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
	Pierre	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
	New Underwood	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
2015	Onida	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
	Pierre	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
	New Underwood	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76
	Caputa	no-till, long-term	wheat	oilseed	Mycogen MY8H456CL	high-oleic	76

[†] Long-term no-till are fields that have been in a no-till tillage system for six or more years.