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Response of Sunflower to Nitrogen and Phosphorus in North Dakota

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ABSTRACT

The N and P recommendations for sunflowers growers in North Dakota have not been changed in 30 yr. Twenty-two N and P rate experiments were conducted during 2014 and 2015. The objective was to determine the response of seed yield, oil concentration, and lodging to available N and P. In 2014 studies were a randomized complete block split plot with N rate as main plots and P rate as subplots. Nitrogen was applied at rates of 0, 45, 90, 134, 179, and 224 kg N ha^{-1}. Phosphorus was applied to establish P rates of 0, 13, 26, and 39 kg P ha^{-1}. In 2015, the field design included only 0 and 26 kg P ha^{-1}. Experiments were taken to yield and lodging was recorded at harvest. Oil seed sunflower (17 experimental locations) was also analyzed for oil concentration. The N response of sunflower seed yield was quadratic. Increased N rate resulted in lower oil concentration in half of the oilseed experiments. Increased N rate was linearly related to increasing lodging at several sites. Phosphate fertilization had little effect on seed yield, oil concentration, and lodging, despite many of the sites having soil P levels considered 'low'. Future N rate recommendations should be based on seed yield response with increasing N and oil concentration reduction with increasing N for oilseed sunflower. A limit to maximum N rate should also be considered because of the lodging risk in this wind-plagued region.

Core Ideas

- Nitrogen availability and fertilization can increase sunflower see yield.
- Nitrogen fertilization may decrease oil concentration of oilseed sunflower.
- Nitrogen fertilization increases sunflower lodging risk in windy regions.

Sunflower (*Helianthus annuus* L.) is native to North America. American natives first cultivated sunflower 5000 yr ago in the present-day southwest United States (Semeslczi-Kovacs, 1975). Sunflower spread to the north and east in North America, where it was domesticated 4000 yr ago (Blackman et al., 2011). Sunflower is a relatively new commercial crop to the United States, with commercial cultivation beginning in the 1970s. Sunflower has since become an important crop in the northern Great Plains regional states of North Dakota, South Dakota, and Minnesota, with additional production in Kansas, Colorado, and Texas. Sunflower production has evolved with innovations in production and genetics that have resulted in improved yield (Fig. 1) (USDA-NASS, 2015; Hulke and Kleingartner, 2014). As of 2015, approximately 85% of US sunflower production is in the northern Great Plains (USDA-NASS, 2015) and sunflower is considered among the most important crops grown for edible oil in the world (Putt, 1997).

Sunflower fertility requirements of N and P in the northern Great Plains were determined through establishment of soil test calibration studies and associated determination critical N and P soil test values, with yield and oil concentration responses when it first became a commercially important crop. Yield components of sunflower include seed number per plant and seed size. Oil concentration is also a consideration for oilseed sunflower (Connor and Hall, 1997). Increasing N supply increases seed number per head, seed mass and overall oil yield (Abbadi et al., 2008; Connor and Sadras, 1992; Hocking and Steer, 1989; Steer and Hocking, 1984).

Nitrogen trials were conducted in North Dakota from 1971 to 1983 on dryland sunflower and from 1977 to 1983 for irrigated sunflower (Zubriski and Moraghan, 1983). In these experiments, sunflower yield increased and oil concentration decreased with increasing total known available N. In Minnesota, a seed yield of 2900 kg ha^{-1} required 135 kg ha^{-1} of N for oilseed sunflower and 147 kg ha^{-1} of N for confectionary sunflower (Faulkner, 1977), leading to the recommendation that oilseed and confectionary sunflower required 5 kg N ha^{-1} to produce each 100 kg ha^{-1} of seed. In Minnesota, Robinson (1973a) recorded no oil sunflower seed yield increase with N fertilizer; however, subsequent studies found yield increases

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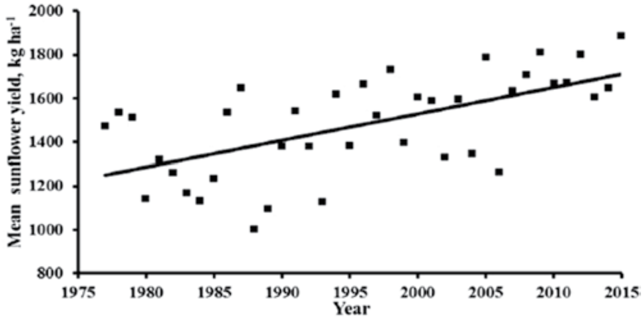

Fig. 1. Mean sunflower seed yield in the United States by year.

with N fertilization (Robinson 1973b), concluding that sunflower required 1 kg ha^{-1} N for each 10 kg ha^{-1} sunflower seed yield. Vigil et al. (2001) published results from Colorado, concluding that sunflowers needed about 56 kg N ha^{-1} per 1120 kg ha^{-1} of potential sunflower yield. This recommendation was updated when the results of a 7-yr study in the High Plains region indicated that a 1120 kg ha^{-1} sunflower yield required between 67 and 78 kg N ha^{-1} (Vigil, 2009).

Many additional experiments have investigated N influence on sunflower worldwide (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., 1984; Kandil, 1984; Hussein et al., 1980) finding mixed results, but usually finding increased yield and decreased oil concentration with increasing N rate.

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

$$\text{N required, kg ha}^{-1} = (0.05 \times \text{YG}) - (\text{NO}_3^{-} - \text{N}_{0-60\text{cm}})$$

where YG is the yield goal in kg ha^{-1} and $(NO_3^{-} - N_{0-60cm})$ represents the kg ha^{-1} residual NO_3^{-}–N present in the soil from the depth of 0 to 60 cm from a preplant soil test. This formula was later amended to reduce N fertilizer recommendations to sunflowers with recognition of a previous crop credit, such as after soybean or after alfalfa (Franzen, 2013).

Soil tests for sunflower are conducted prior to planting in the northern Great Plains to a 15-cm depth for soil test P and a 60-cm depth for NO_3^{-}–N (Hergert, 1987). In general, consideration of the use of soil testing for residual soil nitrate N consists of measuring NO_3^{-}–N_{60cm} using the nitrate–electrode method or cadmium reduction method (Gelderman and Beegle, 1998), and crediting this N against the total N recommendation. Recommendations to sunflower growers for N and P fertilization that resulted from these experiments have not changed significantly for more than 30 yr (Dahnke et al., 1981; Gerwing and Gelderman, 2005; Franzen, 2010; Kaiser et al., 2011).

However, soil test calibrations should be continually updated (Peck and Soltanpour, 1990; Heckman et al., 2006). In the case of sunflowers in North Dakota, cultivars are different than 30 yr ago, and tillage practices have changed to greater adoption of no-till production systems. In contrast to Eq. 1, May et al. (2010) indicated a curvilinear sunflower yield response to N in a series of N rate trials in Saskatchewan. The regression equation was $Y = 1.00 + 0.0045\,(N) - 0.0000142\,(N)^2$, $R^2 = 0.81$; where Y is yield in kg ha^{-1}, and N is N rate in kg ha^{-1}. The curvilinear response to N rate resulted in diminishing economic returns from the application of N with higher yield and N rate.

The objective of this research was to develop the basis for modern N and P recommendations for sunflower in North Dakota from fertilizer N and P rate experiments on sunflower yield and oil concentration.

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} resulted in insignificant ($P < 0.05$) yield differences of 2643 and 2742 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 (1984) indicated that there was no correlation between P soil test and response of sunflower seed yield and oil yield to P fertilizer, and also that the sunflower plant was able to obtain sufficient supplies of P from soil sources. Although there was little experimental data supporting the use of P fertilizer for sunflower, North Dakota continued to recommend P fertilizer through 2014, with a critical Olsen soil test P level of 16 mg kg^{-1} (Franzen, 2013).

The objectives of this study are to determine the yield response of sunflower to N and P, and to determine the N rate recommendation factors that should be considered when developing a yield- and economic-based N and P recommendation system for commercial sunflower production.

METHODS

Nitrogen and P rate trials with confectionary and oilseed sunflower were taken to yield at 23 experimental locations in North Dakota in 2014 and 2015 (Tables 1 and 2). Each experimental location was established with a farmer cooperator 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 subplots. Nitrogen rate was chosen as the main plot, because previous research has found little yield response to P rate in sunflower, whereas the yield and oil changes with N rate might be large and experimental error would then also be expected to be larger. Experimental units (subplots) were 3.05 × 9.1 m long. Each experimental unit contained four sunflower rows with 0.76-m spacing between rows.

Nitrogen treatments in 2014 and 2015 were check (0 added N), 45, 90, 134, 179, and 224 kg N ha^{-1}. Nitrogen fertilizer was applied by hand, pre- or post-plant within a week of planting; in 2014 as either ammonium nitrate or Agrotain (Koch Agronomic Services, Wichita, KS) treated urea and in 2015 as either ammonium nitrate or Limus (BASF, Research Triangle Park, NC)

Table 1. North Dakota 2014 locations and soil information.

Location	Category	GPS coordinate (NW site corner)	Soil series†	Tillage‡	Previous crop
Amidon	West long-term no-till	46°19´26.912″N 103°23´34.870″W	Galva silt loams	No-tillage	Wheat§
Beach	West long-term no-till	46°49´02.928″N 103°59´35.290″W	Galva silt loams	No-tillage	Wheat
Belfield	West long-term no-till	47°04´52.539″N 103°09´53.605″W	Lihen loamy sands	No-tillage	Wheat
Cummings	East conventional	47°30´43.150″N 97°06´44.884″W	Glyndon silt loams	Conventional	Corn
Dickinson North	West long-term no-till	47°03´53.825″N 102°50´37.729″W	Regent silty clay loams	No-tillage	Corn
Dickinson South	West long-term no-till	46°43´42.114″N 102°48´38.101″W	Lawther silty clays	No-tillage	Corn
Hazelton	West long-term no-till	46°20´21.252″N 100°11´30.253″W	Amor loams	No-tillage	Corn
Hazen	West long-term no-till	47°29´28.192″N 101°30´14.330″W	Williams loams	No-tillage	Wheat
Heil	West long-term no-till	46°20´31.580″N 101°41´01.112″W	Vebar fine sandy loams	No-tillage	Wheat
Valley City	East long-term no-till	46°52´58.010″N 97°54´53.505″W	Barnes loams	No-tillage	Wheat
Walcott	East conventional	46°29´10.505″N 97°03´10.231″W	Glyndon loams	Conventional	Corn

† Galva: fine-silty, mixed, superactive, mesic Typic Hapludolls; Lihen: sandy, mixed, frigid Entic Haplustolls; Glyndon: coarse-silty, mixed, superactive, frigid Aeric Calciaquolls; Regent: fine, smectitic, frigid Vertic Argiustolls; Williams: fine-loamy, mixed, superactive, frigid Typic Argiustolls; Vebar: coarse-loamy, mixed, superactive, frigid, Typic Haplustolls; Barnes: fine-loamy, mixed, superactive, frigid, Calcic Hapludolls.

‡ These no-tillage sites are in fields that have been in a no-tillage system continuously for six or more years.

§ Wheat: spring wheat (*Triticum aestivum* L. emend Thell); corn: *Zea mays*, L.

Table 2. North Dakota 2015 location and soil information.

Location	Category	GPS coordinate (NW site corner)	Soil series†	Tillage‡	Previous crop
Amenia	East conventional	47°02´05.939″N 97°11´38.605″W	Fargo silty clay loams	Conventional	Soybean
Amidon	West long-term no-till	46°19´26.995″N 103°21´53.946″W	Chama silt loams	No-tillage	Wheat§
Beach	West long-term no-till	46°51´12.289vN 103°55´29.614″W	Sen silt loams	No-tillage	Wheat
Belfield	West long-term no-till	47°03´08.192″N 103°14´05.589″W	Grail clay loams	No-tillage	Wheat
Bottineau North	East long-term no-till	48°49´19.524″N 100°42´59.213″W	Fargo silty clay loams	No-tillage	Wheat
Bottineau South	East long-term no-till	48°49´13.625″N 100°42´41.111″W	Fargo silty clay loams	No-tillage	Wheat
Coleharbor	West long-term no-till	47°31´49.819″N 101°16´41.822″W	Williams loams	Strip-tillage	Corn
Dickinson	West long-term no-till	46°59´43.425″N 102°46´40.872″W	Amor loams	No-tillage	Corn
Elgin	West long-term no-till	46°26´34.239″N 101°54´02.755″W	Lawther silty clays	No-tillage	Wheat
Linton	West long-term no-till	46°13´01.639″N 100°03´50.523″W	Straw silt loams	No-tillage	Soybean
Valley City	East long-term no-till	46°52´36.844″N 97°56´24.370″W	Fordville loams	No-tillage	Wheat
Walcott	East conventional	46°35´16.441″N 97°02´55.626″W	Hecla fine sandy loams	Conventional	Corn

† Fargo: fine, smectitic, frigid Typic Epiaquerts; Chama: fine-silty, mixed, superactive, frigid Typic Calciustolls; Sen-Fine: silty, mixed, superactive, frigid Typic Haplustolls; Grail: fine, smectitic, frigid Pachic Vertic Argiustolls; Williams: fine loamy, mixed, superactive, frigid Typic Argiustolls; Amor: fine, loamy, mixed, superactive, frigid Typic Haplustolls; Lawther: fine, smectitic, frigid Typic Haplusterts; Fine: loamy, mixed, superactive, frigid Cumulic Haplustolls; Fordville: fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Hapludolls; Hecla: sandy mixed, Oxyaquic Hapludolls.

‡ These no-tillage/strip-tillage sites are located in fields that have been in a continuous no-tillage system for six or more years.

§ Wheat: spring wheat (***Triticum aestivum*** L. emend Thell); corn: ***Zea mays***, L.; soybean: ***Glycine max***, Merrill.

treated urea to limit ammonia volatility losses. Treatments at conventional tillage sites were incorporated by the cooperator within a week of application. At no-tillage sites, the N fertilizer was surface applied with no mechanical incorporation. Within main plots in 2014, four P treatment rates were applied as subplots; check (no added P), 34, 67, and 101 kg P_2O_5 ha^{-1} (0, 13, 26, and 39 kg P ha^{-1}). As a result of the non-response to P fertilizer from 2014 data, only two P treatment rates were applied as subplots in 2015; check (no added P) and 67 kg P_2O_5 ha^{-1} (26 kg P 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}, S concentration 200 mg kg^{-1} gypsum). In 2014 N rate trials in corn, S deficiency became a problem in other studies on a wide range of soils from loam to clay, and organic matter as great as 50 g kg^{-1} in the 0–15 cm soil depth. Therefore, as a standard protocol beginning in 2015, a base rate of S as gypsum fertilizer was applied to all soil fertility N and P trials.

Composite soil samples from eight soil cores obtained at the 0–15 cm and 15–60 cm depths were collected at each experimental location before fertilizer application to determine NO_3^-–N_{0-60cm} (nitrate–electrode detection; Gelderman and Beegle, 1998), available soil K (Warncke and Brown, 1998), plant available Olsen method extraction P (Frank and Denning, 1998), soil pH (Peters et al., 2015), organic matter, loss on ignition (Combs and Nathan, 1998) and EC (electrical conductivity/soluble salts; Whitney, 1998). Soil test results for each site–year are listed in Table 3. Row width of each site and GPS coordinates are listed in Tables 4 and 5.

Cultivar and agronomic information relevant to experimental locations are provided in Table 4. Replications were separated at each trial location by either a 1.50-m or 3.0-m alleyway where no fertilizer was applied. Alleyways were cleared of growing sunflowers between the V4–V6 vegetative growth stages. There was also a buffer zone of between 1.5 m and 3.0 m width, around the outside of each experimental area to prevent errant N or P fertilizer from the field fertilizer application from contaminating the experimental treatment areas. Weeds were removed by hand, if necessary, at V4–V6, V12, and later growth stages from the trial area. Herbicide was applied at the discretion of the cooperator.

One of the two middle rows from each experimental unit was harvested by clipping the sunflower head from the stalk as close to the head as possible, and putting the heads into burlap bags, and removing from the field. The outside sunflower heads at each end of the row were not harvested. Lodged sunflowers, defined as sunflowers leaning more than a 45° 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 between 8 and 10% moisture prior to being threshed. Threshing of sunflower heads was conducted using a 1985 Hege plot combine in 2014 and a 2015 model Almaco (Almaco, Nevada, IA) 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 subsample using a Dickey-John GAC500XT moisture and test weight meter

Table 3. North Dakota 2014 soil analysis of selected factors for experimental locations.

Year	Location	NO_3–N†	P	K	pH	EC	OM
2014	Amidon	43	5	250	8.0	0.23	33
	Beach	32	14	280	6.0	0.12	31
	Belfield	39	17	260	6.2	0.10	40
	Cummings	205	21	145	7.8	0.37	40
	Dickinson North	149	32	NA‡	NA	NA	30
	Dickinson South	31	8	242	6.3	0.27	26
	Hazelton	85	19	385	5.7	0.26	52
	Hazen	92	18	265	6.8	0.37	40
	Heil	116	9	250	7.8	0.30	42
	Valley City	32	14	NA	NA	NA	30
	Walcott	68	12	190	8.2	0.10	25
2015	Amenia	63	28	396	7.3	0.44	55
	Amidon	40	3	NA	NA	NA	30
	Beach	45	2	113	8.1	0.25	26
	Belfield	54	8	148	6.4	0.13	25
	Bottineau North	37	7	430	7.8	NA	52
	Bottineau South	47	8	465	7.5	NA	49
	Coleharbor	101	8	250	6.2	0.27	41
	Dickinson	94	6	122	5.9	0.17	34
	Elgin	94	12	325	5.8	0.26	56
	Linton	28	7	290	6.9	0.28	44
	Valley City	26	21	135	6.9	NA	31
	Walcott	94	11	95	6.2	0.10	15

† NO_3–N represents NO_3^-–N_{0-60cm} in kg ha^{-1} except only a 30 cm depth obtained at Walcott 2015 (NO_3^-–N_{0-30cm}) due to ice below 30 cm preplant. P mg kg^{-1}, K mg kg^{-1}, EC mmoh cm^{-1}, OM g kg^{-1}.

‡ NA: analysis was not conducted for that site.

(Dickey-John, Auburn, IL). Yields were adjusted to 10% moisture across all site-years. A nuclear magnetic resonance (NMR; MQC, Oxford Instruments, Abingdon, Oxfordshire, UK) oil test was conducted on all high oleic or NuSun oilseed sunflower seeds (kernel plus hull) at the USDA Sunflower Testing Center, Fargo, North Dakota, to obtain the oil percentage adjusted to 10% moisture.

Statistical analysis for analysis of variance was conducted using SAS 9.3 for Windows (SAS Institute, Inc. 2013, Cary, NC) using PROC MIXED to determine the effect of N, P, and N × P interaction on sunflower yield and soil concentration. Tukey's multiple range test was used to test differences in yield and quality means between treatments. Regression analyses to determine the best-predicting model relation (coefficient of determination, r^2) sunflower yield, oil concentration, or lodging with N rates were performed using Microsoft Excel 2010 (v.14.0, Redmond, WA). 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_{0-60}, resulting in a value for total known available N.

The categorization of site–years into eastern and western North Dakota was based on multiple regression analysis, but the logic behind analyzing data from experiments in these regions separately is due to historical 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

Table 4. North Dakota 2014 and 2015 sunflower cultivar and agronomic information.

Year	Location	Planting date	Cultivar	Type†	Row width	Harvest date
2014	Amidon	23 June	Mycogen 8H288CLDM	Oil	76	2 Oct.
	Beach	4 June	Pioneer P63ME80/N472	Oil	76	10 Oct.
	Belfield	31 May	Mycogen 8H288	Oil	76	2 Oct.
	Cummings	8 June	Royal Hybrid 1121	Confection	76	21 Oct.
	Dickinson North	5 June	Red River 2215	Confection	76	9 Oct.
	Dickinson South	8 June	Pioneer P63ME80	Oil	76	9 Oct.
	Hazelton	1 June	Undisclosed	Confection	76	29 Sept.
	Hazen	4 June	Pioneer P63HE60	Oil	25	12 Oct.
	Heil	10 June	Croplan 3080	Oil	76	9 Oct.
	Valley City	20 May	Syngenta 3495CLDM	Oil	76	23 Sept.
	Walcott	31 May	Royal Hybrid 400CL	Confection	76	26 Sept.
2015	Amenia	11 June	NK 7111	Oil	56	15 Oct.
	Amidon	26 Apr.	Mycogen 8H288CLDM	Oil	76	21 Sept.
	Beach	21 May	Pioneer P63HE60/N393	Oil	76	22 Sept.
	Belfield	11 May	Mycogen 8H2888	Oil	76	21 Sept.
	Bottineau North	29 May	Mycogen 288	Oil	76	8 Oct.
	Bottineau South	30 May	Mycogen 288	Oil	76	8 Oct.
	Coleharbor	15 June	Mycogen 288	Oil	76	15 Oct.
	Dickinson	30 May	Red River 2215	Confection	76	6 Oct.
	Elgin	26 May	Croplan 3080	Oil	76	1 Oct.
	Linton	30 May	Pioneer 63HE60	Oil	76	29 Sept.
	Valley City	4 June	Syngenta 3495CLDM	Oil	76	7 Oct.
	Walcott	31 May	Royal Hybrid 400CL	Confection	76	26 Sept.

† Oil is oilseed.

Table 5. Mean seed yield of oilseed and confection sunflower and oil concentration of oilseed sunflower in check treatment and in the N treatment that resulted in highest seed yield for the location, arranged by analysis category. Nitrogen rate to achieve highest seed yield within location was the sum of N rate applied as fertilizer, preplant residual nitrate N, and a 44 kg N ha^{-1} credit (Franzen, 2013) if sunflower followed soybean (Linton location).

Analysis category†	Year/Location	Check ‡ Treatment N kg ha^{-1}	Seed yield at check N rate kg ha^{-1}	Oil at check N rate mg kg^{-1}	Highest yield/ N rate kg ha^{-1}	Yield difference significance at $P < 0.05$	Oil at highest yield, mg kg^{-1}	Oil difference significance at $P < 0.05$
WO-NT	2014/Amidon	42	1390	391	2200/223	Yes	411	No
	2015/Amidon	80	2440	401	2770/175	No	391	No
	2015/Beach	44	2050	402	2830/135	Yes	384	Yes
	2014/Belfield	38	1770	405	2266/219	Yes	404	No
	2015/Belfield	53	2110	433	2160/189	No	401	Yes
	2014/Dickinson South	30	1530	371	2120/256	Yes	361	No
	2014/Hazelton	85	1640	374	2160/225	Yes	368	No
	2014/Hazen	92	1180	380	1740/310	Yes	369	No
	2014/Heil	115	1820	367	2480/251	Yes	385	Yes
	2015/Coleharbor	102	1900	443	2140/326	Yes	435	Yes
	2015/Elgin	94	2820	436	3390/184	Yes	426	No
	2015/Linton	70	2240	377	2390/118	No	361	Yes
EO-NT	2014/Valley City	34	1420	407	1840/214	Yes	391	Yes
	2015/Bottineau North	75	2540	442	2650/172	No	427	Yes
	2015 Bottineau South	85	1510	437	2410/227	Yes	425	Yes
EO-CT	2015/Amenia	102	1870	378	2540/198	Yes	353	Yes
WC-NT	2014/Dickinson North	132	1720	NR§	2020/239	Yes	NR	NR
	2015/Dickinson	93	3330	NR	3600/229	No	NR	NR
EC-CT	2014/Walcott	68	2410	NR	2570/158	No	NR	NR
	2015/Walcott	93	2900	NR	4130/274	Yes	NR	NR
	2014/Cummings	203	1640	NR	1900/295	No	NR	NR

† WO-NT is western oilseed, no-till; EO-NT is eastern oilseed, no-till; EO-CT is eastern oilseed, conventional till; WC-NT is western confection, no-till; EC-CT is eastern confection, conventional till.

‡ Check Treatment N is total known available N, including residual soil nitrate N to 60 cm and previous crop N credit.

§ NR indicates not relevant, since confection sunflower oil concentration was not determined.

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. Western sites were all located within long-term (6 yr or greater continuous no-till production) fields. Eastern sites contained conventional tillage sites and long-term no-till sites, with different N response curves for oilseed and conventional sunflower yield. Thus, tillage is separated as a category for analysis.

Following preliminary analyses, a quadratic regression model was found to produce the greatest coefficient of determination (r^2) between sunflower yield and total known available N. Sunflower oil concentration was best described by a linear regression model Therefore, quadratic polynomial models for yield and linear models for oil concentration are presented throughout this paper to describe N and P responses of sunflower yield and sunflower oil concentration to total known available N.

Regression analysis for each site-year was conducted using the means of N rate treatments as the dependent variable. The N rate treatment analysis of each site consisted of analysis of the total known available N, which was defined as the sum of the N rate treatment, preplant residual nitrate N, and any anticipated previous crop N credit, such as following soybean. Multiple regression analysis was performed to determine whether the data should be categorized into regions (east and west North Dakota), sunflower seed types (confection or oilseed), and tillage (long-term no-till or conventional tillage) for improved relationships between sunflower seed yield and total known available N. Results indicated that segregation of combined sites into eastern and western North Dakota locations, no-tillage and conventional tillage locations, and oilseed and confection locations improved relationships between yield and available N.

Previous research (Raun et al., 2011; Arnall et al., 2013) has indicated an independence of N rate and yield across locations; therefore, the yield data within each of these sunflower sites was normalized by dividing all yields within a site by the highest yield within the site, resulting in values from 0 to 1 within each site. Analysis of combined sites within categories was also improved by normalizing yields within a site. The normalization equation employed within each experimental location was:

Normalized yield = (Treatment yield/High treatment yield for experimental location)

The normalized yield values were subjected to regression analysis with total known available N to construct response curves of relative yield with available N.

RESULTS AND DISCUSSION

Seed yield at fourteen of 21 experimental locations resulted in a difference between the check (0 kg N ha^{-1}) N rate and the highest yield due to N rate (Table 5). Oil concentration at 8 of 16 locations was decreased with added N in oilseed location experiments, while one location recorded an increase in oil concentration with added N (Heil).

Determining an N response over sites is challenging due to differences in the environmentally dictated yield potential of sites. The site effect includes soil differences, rainfall differences, and possibly varietal differences to N and P fertilization. In exploratory fertilizer rate studies, it would be reasonable to use only one variety to determine if there were a response to a fertilizer over sites (Halvorson et al., 1999). However, the response of sunflower to N rate has been recorded in numerous studies (Zubriski and Zimmerman, 1974; Hussein et al., 1980; Geleta et al., 1997; Halvorson et al., 1999), so it was important in this study to determine responses over many environments.

Determining the response of specific sunflower cultivars with N and P would be of very little practical value, since cultivars are continually upgraded, and have a commercial life of only a few years. However, there are studies that have investigated the response of sunflower cultivars with N rate (Süzer, 2010; Nasim et al., 2012), and found that seed yield response to N rate was similar between oilseed cultivars. The main difference between cultivars was the yield potential within the study environments.

The difference in yield potential with environment is shown for example in the difference in yield in the eastern conventional-till confection sunflower data. The 2015 Walcott location achieved 4130 kg ha^{-1} yield with 274 kg N ha^{-1} while the 2014 Cummings site only achieved 1900 kg ha^{-1} yield with similar (295 kg N ha^{-1}) N supply. Although the coefficient of determination (r^2) of yield comparisons with total available N (the sum of N rate, residual soil nitrate N from the preplant soil nitrate test, and expected N release following certain crops, i.e. previous crop credit) were found to be significant for western oilseed, eastern no-till oilseed, eastern conventional till oilseed and eastern conventional till confection sunflower, the relationship was improved when yield was normalized.

The relationship of sunflower yield with available N is best described by a quadratic curve. The western North Dakota confection sunflower raw data is graphed in Fig. 2a and the coefficient of determination of yield and available N increases with normalization of yield in Fig. 2b. Using the normalized regression on Fig. 2b, the total known available N required to maximize yield in this data set was 262 kg ha^{-1}. Eastern North Dakota confection sunflower raw data is shown in Fig. 3a, and the coefficient of determination of the relationship between yield and available N increases when yields are normalized are shown in Fig. 3b. Using the normalized regression equation in Fig. 3b, the total known available N required to maximize eastern North Dakota confection sunflower under conventional tillage was 350 kg ha^{-1}. Eastern North Dakota no-till oilseed sunflower raw data (Fig. 4a) coefficient of determination is similar, but slightly lower than the normalized data relationship with available N (Fig. 4b). Using the normalized regression equation in Fig. 4b, the total known available N required to maximize eastern North Dakota no-till oilseed sunflower was 300 kg ha^{-1}.

Western North Dakota oilseed sunflower raw data is shown in Fig. 5a, while the coefficient of determination of the relationship of normalized yield and available N increased (Fig. 5b). Using the normalized regression equation from Fig. 5b, the N rate required for maximum sunflower yield was 275 kg ha^{-1}. Only one Eastern North Dakota oilseed sunflower conventional tillage site was investigated. The relationship of yield with available N was strong, with a coefficient of determination of 0.86 (Fig. 6). The N rate required to maximize yield at this site was 225 kg ha^{-1}.

Contrary to the often-used quadratic plateau model (Bullock and Bullock, 2000) in corn (*Zea mays*, L.), which seldom experiences yield decreases with increasing N, except when late-season high winds break over corn stalks and cause harvest losses,

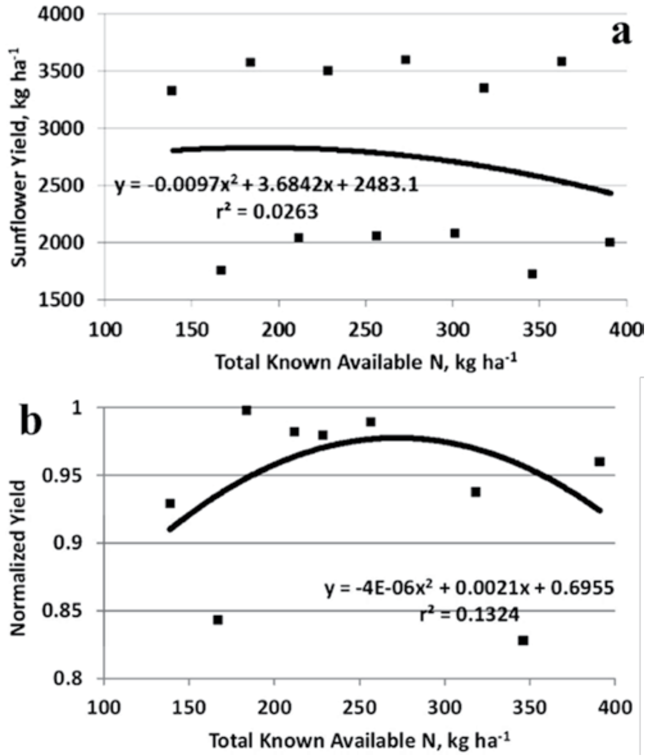

Fig. 2. Response of sunflower seed yield to total known available N using raw yield data (a) and normalized yield data (b) for two western no-till confection sunflower experiments.

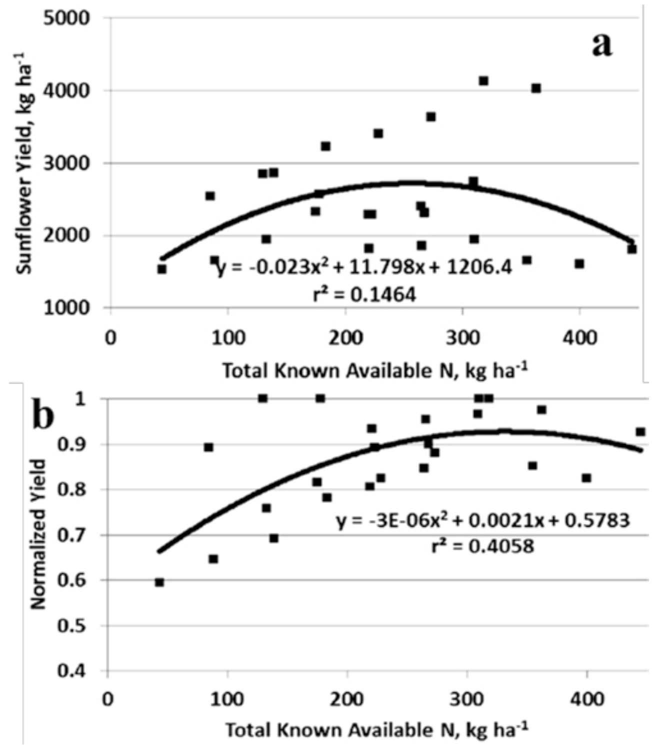

Fig. 3. Response of sunflower seed yield to total known available N using raw yield data (a) and normalized yield data (b) for three eastern conventional till confection sunflower experiments.

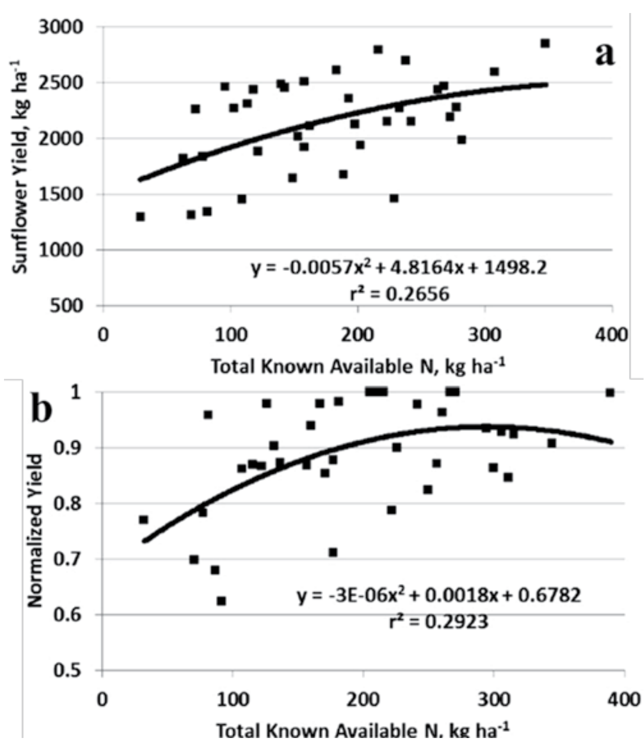

Fig. 4. Response of sunflower seed yield to total known available N using raw yield data (a) and normalized yield data (b) for three eastern no-till confection sunflower experiments.

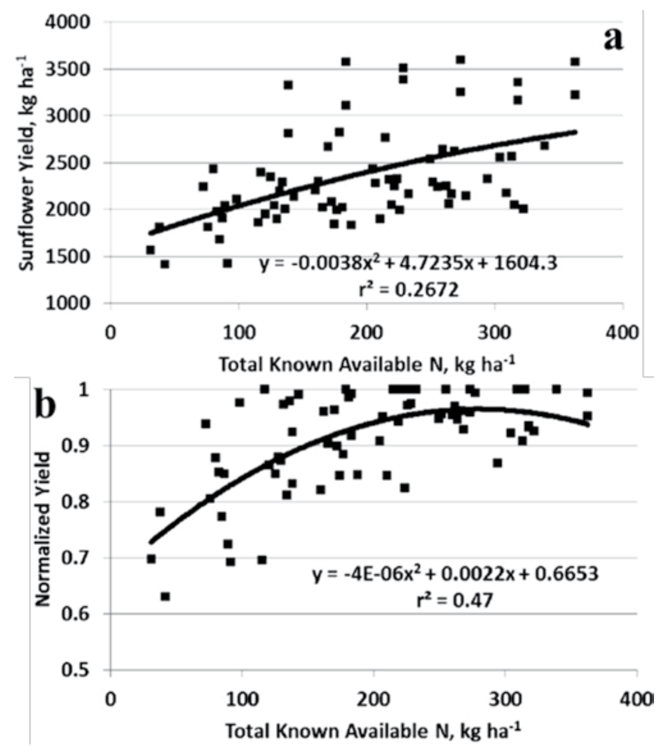

Fig. 5. Response of sunflower seed yield to total known available N using raw yield data (a) and normalized yield data (b) for twelve western no-till oilseed sunflower experiments.

sunflower production in North Dakota is plagued with almost annual high wind events in some fields during critical growth stages, resulting in yield losses due to lodging and subsequent harvest loss. The relationship of N fertilization and sunflower has been observed by other researchers (Scheiner et al., 2002). In the 2015 and 2016 experiments, two sites, Valley City 2015 and Coleharbor 2016, experienced mid-season (July) winds severe enough that the entire plot and long with much of the field was root-lodged, with no N treatment differences. At three sites, Beach in 2015, Bottineau North and Bottineau South in 2016,

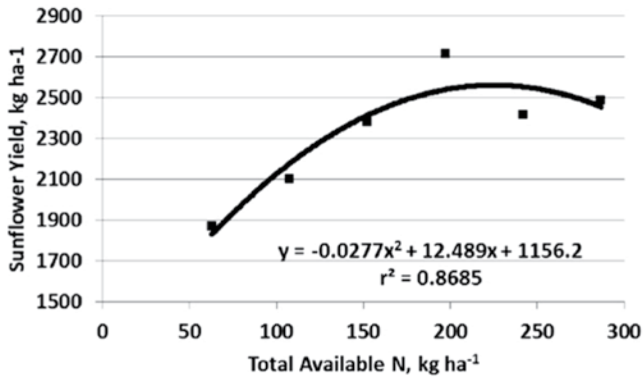

Fig. 6. Response of sunflower seed yield to total known available N using raw yield data for one eastern conventional till oilseed sunflower experiment.

lodging score was affected by N rate. At Beach, 2015, plants lodged at harvest with the check N rate was about 4% With the 179 kg ha^{-1} N rate and 224 kg ha^{-1} N rate, lodging score increased to over 40% Response of lodging to N rate was linear (r^2 = 0.92). At Bottineau North in 2016, lodging with no added N was about 35% At the highest N rate, 224 kg ha^{-1} N, lodging increased to 85% Response of lodging to N rate at Bottineau North, 2016, was linear (r^2 = 0.91). At Bottineau South, 2016, there was again a linear relationship between N rate and lodging score (r^2 =0.97). The check N rate lodging score was about 10%, while the highest N rate lodging score was about 75%

In addition to harvest delays due to lodging, harvest losses would be expected to increase with lodging. In these experiments, sunflower heads were harvested whether in direct contact with the soil or not. Even with complete hand-head harvesting, yields at Beach 2015, Bottineau North 2016 and Bottineau South 2016 tended to decrease after maximum yield was achieved, while yield at sites where lodging was not an issue tended to plateau (data not shown). This suggests that disease might have influenced yield at the sites where lodging was a problem. Evidence for increased disease with N rate comes from a harvest evaluation of sunflower rust incidence and severity at Dickinson in 2016 (Table 6). A photo-image of a back of a sunflower head showing rust pustules was obtained in each experimental unit, and the images were rated on a 0–5 scale, with 0 being no evidence of rust, to 5 being severe rust infection. Sunflower rust ratings increased over the check with the 90 kg ha^{-1} N rate. What these data indicate is that until genetic breeding efforts in sunflower result in greater resistance to lodging, consideration of N rates that moderate lodging in high wind regions like North Dakota should be part of farmer recommendations.

In addition to consideration of increased lodging risk at high N rates, oil concentration of sunflower was reduced by N rate at 8 of 16 sites. The mean decrease in oil concentration at the N rate necessary to maximize yield within an experiment was 18 g kg^{-1}. North Dakota growers are paid a premium for oil concentration delivered to the processor greater than 400 mg kg^{-1}. The premium amounts to 2% of yield delivered multiplied by the difference between 400 g kg^{-1} standard and the oil concentration delivered greater than the standard. Therefore, if the price a sunflower grower would receive at 400 g kg^{-1} was 0.33 US$ kg^{-1}, the price received if the grower delivered 418 g kg^{-1} would be 0.366 US$ kg^{-1}.

Table 6. Sunflower rust severity ratings (Dickinson, 2015).

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

† Values followed by different letters are significantly different at P < 0.05. Rust rating of 0 indicates no rust symptoms on the back of sunflower heads at harvest. Rust rating of 5 indicates a severe infection.

The N recommendation, therefore, for maximizing sunflower production profitability, which is what sunflower growers want to accomplish, must include the yield response of oilseed sunflower to N, the cost of N to achieve maximum yield, and the penalty for N addition that would lead to lower oil content. In addition, consideration of a limit on total available N to sunflower should be made to reduce the risk of lodging.

Although every economic possibility is too much to include in this paper, an example of how this might be used to develop recommendations follows. Using the western North Dakota oilseed normalized formula in Fig. 5b (normalized yield = $-0.000004x^2 + 0.0022x + 0.6653$, where x = N rate), multiplying times the mean of the experiments (2266 kg ha^{-1}) results in the equation: yield = $-0.009064x^2 + 4.9852x + 1508$. For oil concentration, the formula derived from the relationship of N rate with yield is oil concentration is: 450 g kg^{-1} – (N rate × 0. 176).

The gross return from N rate equation considering yield and oil concentration would be:

(Predicted yield × $ kg^{-1} sunflower price) – (N rate × $ N kg^{-1}) + [(Predicted yield × oil concentration) - 400 g kg^{-1})] × ($ kg^{-1} sunflower price × 0.02).

For example, at a sunflower seed price of $0.33 kg^{-1} and N cost of $0.66 kg^{-1}, the optimal N rate would be 124 kg ha^{-1}, with net economic return of $609.95 ha^{-1} (all prices US$). At a sunflower seed price of $0.33 kg^{-1} and N cost of $0.88 kg^{-1}, the optimal N rate would be 87 kg ha^{-1}, with net economic return of $583.63 ha^{-1}. As seed prices increase and N cost decreases, the equation may result in optimal N rates greater than 168 kg ha^{-1}; however, in areas where lodging may be an issue, recommending a limit to N rate of 168 kg ha^{-1} would reduce lodging when high winds occur as sunflower heads are developing. With the old recommendation system, a grower might choose a yield goal of 2200 kg ha^{-1}, with an N rate of 110 kg ha^{-1}. The old N rate formula would tend to underfertilize in the first example and overfertilize in the second example, resulting in economic loss to the grower in each case.

Belfield, 2014 was the only experiment where P application increased yield (Table 7). However, the yield increase from P application would not have justified the cost of P fertilizer. Hazen was the only experiment where oil concentration increased with P rate. At Bottineau North, oil concentration decreased with P rate. Therefore, there is no justification for P application for sunflower in North Dakota intended to increase sunflower yield or oil concentration. The frequency and magnitude of yield response from P application, and its lack of effect on sunflower oil content in oilseed sunflower do not support its economic application.

Table 7. Statistical *P*-values from the application of P fertilizer on sunflower yield and oil concentration.

	Yield	Oil concentration
Site	*P*-value	
Amidon 2014	0.11	0.77
Amidon 2015	0.35	0.60
Beach 2015	0.99	0.75
Belfield 2014	0.01†	0.06
Belfield 2015	0.71	0.55
Valley City 2014	0.61	0.90
Valley City 2015	0.82	0.62
Dickinson South 2014	0.69	0.92
Hazelton	0.96	0.87
Hazen	0.79	0.01†
Heil	0.45	0.91
Amenia	0.21	0.20
Bottineau North	0.06	0.04‡
Bottineau South	0.49	0.69
Coleharbor	0.13	0.86
Elgin	0.73	0.77
Linton	0.59	0.59
Walcott 2014	0.96	NA§
Walcott 2015	0.12	NA
Cummings 2014	0.85	NA
Dickinson North 2014	0.65	NA
Dickinson 2015	0.62	NA

† Indicates response not economic.

‡ P rate reduced oil concentration.

§ NA indicates confection sunflower, no oil concentration.

In the United States, there is little evidence that sunflower responds to P (Zubriski and Zimmerman, 1974; Sundoz, 1984). However, in other countries, responses to P fertilization are more common. In Australia (Lewis et al., 1991), India (Thavaprakash et al., 2002), Nigeria (Adebayo et al., 2010), and Sudan (Salih, 2013), yield increases with P were consistently found. This is why it is important to conduct soil fertility trials in regions of cultivation, because the ability of soils to provide nutrients differ between regions (Roy et al., 2006).

SUMMARY

A series of N and P rate experiments was conducted in North Dakota during the 2014 and 2015 growing seasons that consisted of 17 oilseed sunflower experiments and five confection sunflower experiments. Nitrogen rate and total available N was positively related to sunflower yield. Oil concentration of oilseed sunflower decreased with increasing available N in half of the experiments. Lodging increased linearly with increasing available N at sites where high winds were experienced in mid to late periods of the growing season. Future sunflower N fertilizer recommendations should therefore be based on the seed yield response to N, consideration of the cost of N to achieve the increase, less the penalty from lower oil content from N application in oilseed sunflower. Confection sunflower is not subject to this penalty, so N recommendations may be greater than those for oilseed sunflower. In addition, in regions similar to North Dakota with respect to the occurrence of high winds and lodging almost every year somewhere in the state, a limit to maximum N should be included to reduce lodging risk. Consideration of the yield and oil responses to N in this study result in different optimal N rate recommendations compared to previous formulas, which did not consider economics, were linear response-based, asked the sunflower grower to predict a yield, and did not consider decrease in oil content with N rate nor the effect of wind-induced lodging and subsequent harvest difficulties and yield loss. Phosphorus did not increase sunflower yield or oil content economically at any location; therefore, there is no need to apply P for grower economic gain in sunflower in North Dakota.

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