Title: Advantages of using vegetative indices for variable-rate nitrogen application

Summary (Danish)

Ensartet kvælstof (N) tildeling i traditionel landbrugspraksis håndterer ikke de rumlige og tidsmæssige variationer i N-forsyning og -behov. Talrige undersøgelser har vist, at anvendelse af positionsspecifik N-tildeling med variable doseringer kan reducere den gennemsnitlige N-tilførsel i forhold til standard gødningsstrategi, uden at påvirke udbyttet eller med en lidt positiv indflydelse på udbytte (Argento et al., 2019; Franzen et al, 2019; Diacono et al., 2013; Singh et al., 2011; Havránková et al., 2007 og Tubaña et al., 2008). Præcisionsteknologier kan bruges til at evaluere de positionsspecifikke forhold, og dermed kan der laves justeringer i gødningsstrategien i vækstsæson, som resulterer i en reduktion i den gennemsnitlige N-tilførsel og en højere kvælstofeffektivitet. Franzen (2019) hævder, at hvis N-management i sæsonen er styret ud fra en zone-prøveudtagningsstrategi af jordens nitrat-N med anvendelse af aktive-optiske sensorer, såsom GreenSeeker (Trimble, Inc., Sunnyvale, Californien, USA) og Holland Scientific Crop Circle A470 (Holland Scientific, Lincoln, NE, USA) sensorer, så kan i alt 75% af markens N-variation adresseres ved dyrkning af vårhvede, vinterhvede, majs og solsikke i North Dakota, USA. En nylig undersøgelse med fokus på variabel kvælstofdosering i vinterhvede fandt, at parceller med stor biomasse krævede op til 50% reduktion i kvælstoftildelingen og parceller med lav biomasse krævede op til 15% øget N-tildeling. Som følge af denne variable kvælstoftildeling i forhold til den ensartede standardtildeling, blev der opnået en gennemsnitlig reduktion på 10% i gødningsforbruget (Argento et al. 2019). Samlet set har undersøgelser, der fokuserer på at bruge sensor-baserede N management systemer på hvede fra hele verden, observeret en høj reduktion i anvendelsen af kvælstofgødning (fra 10-80%), besparelser grundet en reduktion i gødningsomkostninger (op til US$60/ha eller 403 kroner/ha), og en højere kvælstofeffektivitet, samtidig med at der ikke er nogen signifikant effekt på hvedeudbyttet i forhold til den ensartede N-management praksis.

Summary (English)

Uniform nitrogen (N) management in conventional agricultural practices fail to address the spatial and temporal variations in N supply and demand. Numerous studies have found that the implementation of site-specific N management using variable rate application can significantly reduce average N application compared to the standard fertilization strategy, without effecting yield or having a slightly positive influence on yield (Argento et al., 2019; Franzen et al., 2019; Diacono et al., 2013; Singh et al., 2011; Havránková et al., 2007 and Tubaña et al., 2008). Precision technologies are used to evaluate site-specific conditions and, thus, adjustments in fertilization strategy can be made in the growing season that result in a reduction in average N application and higher N-use efficiency. Franzen (2019) claims that, if in-season N management is directed by a zone sampling strategy for soil nitrate-N with the use of active-optical sensors, such as the GreenSeeker (Trimble, Inc., Sunnyvale, California, USA), and the Holland Scientific Crop Circle A470 (Holland Scientific, Lincoln, NE, USA) sensors, a total of 75% of field N variability can be addressed for cultivated spring wheat, durum wheat, corn and sunflower grown in North Dakota, USA. A recent study focusing on variable rate nitrogen application in winter wheat found that plots with high biomass required up to 50% N reduction and plots with low biomass required up to 15% increased N. Due to this variable rate application, compared to the uniform standard, there was an average reduction of 10% fertilizer use (Argento et al., 2019). Overall, studies focusing on using sensor-based N management systems on wheat from across the globe have observed a high reduction in fertilizer N use (from 10-80%), improved savings due to a decrease in fertilization costs (up to US$60/ha or 403 Danish Kroner/ha), and higher N use efficiency, all while having no significant effect on wheat yield compared to uniform N management practices.

Demonstrating how precision technologies have improved nitrogen response

In a review by Diacono et al (2013), focusing on precision N management of wheat, they discuss several field studies in which sensor-based N management systems were compared with conventional farming practices. They concluded that, overall, field studies in which sensor-based N management systems were used showed high increases in the N use efficiency of up to 368%, reduced N fertilizer from 10% to about 80% less N and reduced residual N in the soil by 30-50% without reducing yields or influencing grain quality, compared with conventional farming practices. Additionally, precision N management based on real-time sensing and fertilization had the highest profitability of about \$5–60 ha^{-1} (34-403 Danish krone ha^{-1}) compared to uniform applications (Diacono et al., 2013). In a winter wheat field trial in the UK, where Havránková et al (2007) used sensors for N management, they concluded savings 15 kg N ha^{-1} without a negative influence on yield (Diacono et al., 2013). They also reported a fertilizing cost reduction of 7.9% for sensor-based application.

Agrento et al (2019) used the Normalized Difference Red Edge index (NDRE) to make a qualitative assessment of the crop's N status and found a high correlation (R^2=0.53) between N uptake, analyzed from mid-season destructive samples and NDRE measurements. With the use of information from the sensor data, fertilizer N application was reduced up to 35%, compared to uniform fertilizer application of 150 kg N ha^{-1}, without effecting winter wheat yields. Agrento et al (2019)'s study focused on growing winter wheat (*T. aestivum*) in small agricultural fields, in soil characterized as a Gleysol and was not homogenous across fields in Switzerland. To collect spectral information, they used a low-altitude remote sensing UAV platform composed of a multispectral camera mounted on a Quadcopter. The field was flown over on a weekly and bi-weekly basis and information was recorded in four bands if the light spectrum, Green (G) centered at 550 nm, Red (R) at 660 nm, Red Edge (RG) at 735 nm and Near-infrared (NIR) at 790 nm.

Application of N fertilizer was in the form of mineral ammonium nitrate (24% N content), divided in three split applications at different growth stages and consisted of standard (ST), variable rate (VR) and non-fertilized (NF) treatments (Table 1).

Table 1. Fertilization strategy for winter wheat grown in Tanikon, Canton Thurgau, Switzerland which Agrento et al (2019) adapted from Swiss reference Sinaj and Richner (2017) and Levy and Brabant (2016). N_{min} and rates of N fertilizer per treatment in kg N/ha are reported per growth stage in BBCH decimal units (Meier et al., 2009).[1]

	N_{min}	Split 1	Split 2	Split 3	Total
Growth stage	BBCH 20	BBCH 23	BBCH 32	BBCH 45	
Reference	-	80 - N_{min}	60	20	160 - N_{min}
Standard (ST)	44	36	60	20	116
Variable rate (VR)	30 - 85	0 - 50	40 - 70	0 - 20	50 - 132
Non-fertilized (NF)	43	-	-	-	0

[1]Recreated from Agrento et al (2019)

Agrento et al (2019) found a positive correlation (R^2=0.53) between N uptake, analyzed from mid-season destructive samples and NDRE measurements. In their study, they used UAV images to support the decision for spatial distribution of the second and third application of N fertilizer. There was no significant difference between the grain yield obtained in the VR treatment (6.34±0.27 t/ha) and ST treatment (6.23±0.23 t/ha). Argento et al (2019) reports that the average yield for winter wheat in this region is around 7 t/ha of grain and the reduced grain yield is mainly due to drought. This result indicates that the redistribution of N fertilizer in the VR treatment did not affect the yield, while fertilizer use was reduced by 11 kg N ha^{-1} on average compared to the

ST treatment (Table 2). Overall, there was a 10% reduction in fertilizer use is the VR application compared to the uniform standard, with up to a 50% reduction in single plots showing high biomass during the season and up to a 15% increase in the plots that showed low biomass.

Table 2. Nitrogen balance including N applied with the fertilizer and N uptake from the crop harvest.[1]

Treatment	N application	N uptake grain	N uptake straw	N uptake total
	Kg N ha^{-1}			
NF	-	68b	15b	84b
VR	105a[2]	144a	35a	179a
ST	116a	146a	32a	179a

[1]Recreated from Agrento et al., 2019.

[2]Letters represent the level of significance.

This coincides with a study by Singh et al (2011), where they also used a Greenseeker optical sensor to collect NDVI data for estimations of yield potential and to guide N-management, which resulted in improved fertilizer N use efficiency and savings in total applied N fertilizer. Singh et al (2011)'s study was conducted in three different sites in the Indo-Gangetic Plain in northwestern India, a subtropical climate, where they cultivated wheat with different N fertilizer applications and used a handheld GreenSeeker optical sensor unit (NTech Industries Incorporation, Ukiah, CA, USA), to measure spectral reflectance expressed as NDVI. The Green-Seeker has self-contained illumination in both the red (656 nm with about 25 nm full width half magnitude) and NIR (774 with about 25 nm full width half magnitude) bands (Singh et al., 2011). The study sites were at Ludhiana (with mildly alkaline loam soil) from 2005-2006, Karnel (with mildly alkaline sandy loam soil) from 2006-2007 and Modipuram (with alkaline sandy loam soil) from 2006-2007.

Table 3 shows the evaluation of GreenSeeker-based N management in wheat at Ludhiana, India during 2005-2006. The GreenSeeker device used by Singh et al. (2011) uses a patented technique to measure NDVI. Additionally, Singh et al. (2011) used a N fertilizer algorithm applied to the Greenseeker to compute fertilizer N, which was determined based on the difference in estimated N uptake between YP_n and YP_0, and then dividing the difference by the efficiency factor to establish the fertilizer N dose. The evaluations of the Green-Seeker-based N management in wheat at this location and in the two other locations (Karnal, India during 2006-2007 and Modipuram, India during 2006-2007), data not shown is this review, all indicate that appropriate prescriptive fertilizer N applications strategies combined with Greenseeker optical sensor-guided fertilizer N application, at 2nd and 3rd irrigation stages, resulted in increased fertilizer N use efficiency at optimum yield levels due to lower rates of total N application. The results of using the GreenSeeker and the grain yields of wheat show that the corrective N dose for obtaining high yield levels was determined by timing of prescriptive N doses along with time of application of corrective dose (Singh et al., 2011). In all locations, the GreenSeeker-guided fertilizer N application at Feekes growth stages 5-6 and 7-8, resulted in improved N use efficiency and savings in total fertilizer N application, with no reduction of yield. For example, in the trial at Ludhiana, India during 2005-2006, N fertilizer application was reduced up to 18% (applying a total of 98 kg N ha^{-1}) compared to the uniform application of 120 kg N ha^{-1} and up to 35% (applying a total of 98 kg N ha^{-1}) compared to the uniform application of 150 kg N ha^{-1}, without affecting winter wheat yield.

This reduction of N fertilization without effecting yield, is with the exception of 80 kg N ha^{-1} or less because in Ludhiana, India from 2005 to 2006 the prescriptive dose of 80 kg N ha^{-1} and prescriptive dose of 40 kg N ha^{-1} along with sensor-guided N application at Feekes 5-6 growth stage resulted in significantly less grain yield of wheat compared to the treatment receiving the blanket recommendation (Table 3).

Table 3. Evaluation of GreenSeeker-based N management in wheat (cultivar PBW 343) at Ludhiana, India from 2005 to 2006 by Singh et al (2011). YP_0 is the yield potential with no additional fertilizer N applied, RI is the response index (RI_{NDVI}), AE is the agronomic efficiency of applied N (kg grain kg^{-1} N applied), RE is the percent recovery efficiency of applied N, PE is the physiological efficiency (kg grain kg^{-1} N) and LSD is the least significant difference.

Treat-ment	Fertilizer N application (kg N ha^{-1})					YP_0 (Mg ha^{-1})	RI	Grain yield (Mg ha^{-1})	Total N uptake (kg ha^{-1})	AE	RE (%)	PE
	Basal at sowing	CRI[b], 1st irrigation	Feekes 5-6 stage, 2nd irrigation	Feekes 7-8 stage, 3rd irrigation	Total							
1	0	0	-	-	0			1.52	31.9			
2	60	60	-	-	120			4.35	103.2	23.6	59.2	39.9
3	75	75	-	-	150			4.41	110.3	19.3	52.3	37.1
4	60	0	17[a]	-	77	3.25	1.16	3.66	73.1	27.8	53.2	52.2
5	80	0	12[a]	-	92	3.52	1.11	3.80	87.8	24.8	60.9	40.7
6	100	0	10[a]	-	110	3.61	1.09	4.20	95.2	24.4	57.3	42.5
7	40	40	3[a]	-	83	4.02	1.02	3.81	88.5	27.6	68.1	40.6
8	50	50	0[a]	-	100	4.30	0.98	4.32	98.8	28.0	67.0	41.8
9	60	60	0[a]	-	120	4.20	0.99	4.39	105.4	23.9	61.3	39.3
10	60	0	-	29[a]	89	2.98	1.30	3.99	94.2	27.8	69.7	39.4
11	80	0	-	24[a]	104	3.24	1.24	4.13	97.6	25.1	63.5	40.5
12	100	0	-	21[a]	121	3.43	1.19	4.29	102.4	22.9	58.3	39.2
13	40	40	-	18[a]	98	3.62	1.15	4.27	100.5	28.1	70	39.9
14	50	50	-	12[a]	112	3.84	1.10	4.35	108.5	25.3	68.4	36.8
15	60	60	-	15[a]	135	3.77	1.12	4.40	115.2	21.3	61.5	34.7
LSD (p=0.05)								0.367	11.04	3.03	9.52	4.41

[a]GreenSeeker-guided N application
[b]Crown root initiation stage

This reduction in the use of fertilizer N by using sensor-based technology and algorithms was also concluded in a study by Ortiz-Monasterio and Raun (2007), where they concluded that on average small-scale farmers saved 69 kg N ha^{-1} and large commercial farmers saved 76 kg N ha^{-1}, without effecting wheat yield in north-western Mexico. This study was conducted in 2002-2004, where they also used the GreenSeeker (NTech Industries, Inc., Ukiah, CA, USA). Table 4 shows the basal N rate used by farmers, the total amount of N applied in the N-Rich strip (where all N was applied at planting), the total N rate used in the area managed by the sensor and the total N rate used in the area where N was conventionally managed, in 13 of Ortiz-Monasterio and Raun (2007)'s on-farm validation trials. Their results indicate that farmers using conventional N management used an average N rate of 226 kg N ha^{-1}, whereas the farms with managed N application by the GreenSeeker recommendation used only 157 kg N ha^{-1}. In addition to saving 69 kg N ha^{-1} of fertilizer, there was no effect on yield.

Table 4. Results from 13 on-farm validation trials showing the basal N rate used by farmers, the total amount of N applied in the N-Rich strip, the total N rate used in the area managed by the sensor and the total N rate used in the area where N was conventionally managed.[1]

Location	Basal N rate under conventional N management	N-rich strip	Total N rate sensor area	Total N rate conventional N management
	kg N ha^{-1}			
Valenzuela	134	206	134	160
Amaya	92	276	92	230
Dabdoub	175	220	175	220
Castro	92	184	92	184
Pablos	0	207	198	207
Lopez de Lara	123	273	123	246
Felix	180	230	180	220
Arvizu	204	366	204	245
Dabdoub	19	275	219	275
Gallegos	160	344	160	252
Miranda	138	276	138	198
Perez	149	298	174	247
Nery	147	440	147	253
Mean	137	277	157	226

[1]Recreated from Ortiz-Monasterio and Raun (2007).

During wheat crop cycle 2005-2006, Ortiz-Monasterio and Raun (2007) established 8 'technology transfer trials' where wheat was grown on farmers' fields about 10 ha each. These trials further demonstrated that, by using sensor-based N management, large commercial farmers could improve their farm income by US$50/ha by saving money on N fertilizer. The fertilizer application recommendations were calculated using NDVI measured towards the end of tillering and beginning of stem elongation (Zadoks growth stage 31) in wheat. Their results indicated that the average N rate on the conventional N management farms was 203 kg N ha^{-1} and only 127 kg N ha^{-1} on the farms managed by sensors (76 kg N ha^{-1} less) (Table 5). The results show that the sensor areas often yielded slightly less than the conventional farmers' areas, however the economic analysis indicated that the sensor areas were always significantly more profitable due to savings in fertilizing costs (Ortiz-Monasterio and Raun, 2007).

Table 5. Results from 8 technology transfer trials showing the N rate used in the sensor areas, the area under farmer's management and the N-rich strip, the area planted of each of these plots, the grain yield, fertilizer costs, income from wheat sales, amount of N saved using the sensor and improvement in farm income by using the sensor compared to the conventional farmer's management.[1]

Block number	Fertilizer rate	Grain yield	Fertilizer cost[2]	Income from yield[3]	N savings	N savings	Improvement in farm income with sensor use
	kg ha^{-1}	t ha^{-1}	US$/ha			kg N ha^{-1}	US$/ha
B. 1003	138 Sensor	7.13	113	1362	63	82	20
	220 Farmer	7.36	176	1405			
	230 N-rich strip	7.43	188				
B. 2128	75 Sensor	7.35	61	1403	58	75	56
	150 N-rich strip	7.36	123	1405			

B. 1110	138 Sensor	6.97	113	1331	46	60	12
	198 Farmer	7.15	159	1366			
	276 N-rich strip	7.38	226				
B. 909	115 Sensor	7.28	94	1390	63	82	26
	197 Farmer	7.48	157	1427			
	230 N-rich strip	7.73	188	1476			
B. 516	150 Sensor	8.05	123	1536	77	100	104
	250 Farmer	7.90	200	1509			
	243 N-rich strip	8.14	199				
UCAH	92 Sensor	7.44	75	1421	71	92	71
	92 Sensor	7.57	75	1444			
	184 Farmer	7.57	151	1444			
	276 N-rich strip	7.29	226				
B. 1924	160 Sensor	7.30	131	1394	29	37	86
	197 Farmer	7	160	1336			
	217 N-rich strip		178				
B. 1107	148 Sensor	7.68	121	1466	63	82	45
	230 Farmer	7.77	184	1484			
	241 N-rich strip	7.82	197				
Average							53

[1]Recreated from Ortiz-Monasterio and Raun (2007).

[2]Fertilizer cost on January 2006: urea US$0.82/kg N and Anhydrous ammonia US$0.78/kg N.

[3]Price of wheat per metric ton: US$191

[4] For all of the calculations, the exchange rate during May 2006 was used (1 US$ = 11pesos)

The results from Ortiz-Monasterio and Raun (2007)'s study are consistent with a study by Tubaña et al. (2008), where they also found that fields using fertilization optimization algorithm-based N rate recommendations had slightly less grain yield than fields in the conventional (fixed) N treatments, however the differences in yield were not significant and the fields with N rate recommendations were more profitable because farmers used significantly less N fertilizer. Tubaña et al. (2008)'s study was conducted on winter wheat fields in 3 different locations in Oklahoma, USA from 2004-2006. The trials sites where 1) Chickasha with soil series 'Dale silt loam' 2) Tipton with soil series 'Tillman-Hollister clay loam' and 3) LCB with soil series 'Pulaski fine sandy loam'. N fertilization optimization algorithm-based N rate recommendations were determined midseason using the average NDVI at Feekes growth stage 5. Tubaña et al. (2008) used an NDVI-derived-INSEY (in-season estimated yield), calculated by dividing NDVI measured at Feekes growth stage 5 by the number of days from planting to sensing, where growing degree days was greater than zero. This index predicts biomass produced on a daily basis and was used to predict yield potential using the current algorithm for wheat (Tubaña et al., 2008). The nitrogen fertilization optimization algorithm (NFOA) used in the study provided spatial variability using the coefficient of variations (CV) from NDVI readings, and Tubaña et al. (2008) used this to adjust N rate recommendations. Their results indicated that, in all 3 trial locations, treatments with N fertilization optimization algorithm-based N rate recommendations used on average 40% less total applied N compared to the 90 kg N ha^{-1} fixed rate, without having a significant effect on grain yields.

Conclusion

Sensor-based N management results in a significant reduction of N fertilizer use and improved N-use efficiency, with either no effect or a positive effect on yield, compared to conventional (uniform) farming practices.

Studies on cultivating wheat have demonstrated that when using variable rate application, plots with high biomass required up to 50% N reduction and plots with low biomass required up to 15% increased N, with these sensor recommendations not effecting yield while saving 10% of N fertilizer, compared to uniform treatments. Furthermore, studies have shown that farmers can significantly improve their income, due to the reduction of fertilizing costs. Precision technologies allows for an understanding of field conditions across the field and, therefore, the farmer can reduce their fertilizer N application.

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