Archives of Agronomy and Soil Science
Vol. 54, No. 5, October 2008, 481–491

Determination of optimum resolution for predicting corn grain yield using sensor measurements

Byungkyun Chung[a], Kefyalew Girma[a], Kent L. Martin[b], Brenda S. Tubaña[c], Daryl B. Arnall[a], Olga Walsh[a] and William R. Raun[a]*

[a]*Plant and Soil Sciences, Oklahoma State University, Stillwater, Oklahoma;* [b]*Department of Agronomy, Kansas State University, Manhattan, Kansas;* [c]*School of Plant, Environmental and Soil Sciences, Louisiana State University AgCenter, Baton Rouge, Louisiana, USA*

(*Received 28 December 2007; final version received 21 May 2008*)

Identifying the optimum resolution where differences in corn (*Zea mays* L.) grain yields are detectable could theoretically improve nitrogen (N) management, thereby resulting in economic and environmental benefits for producers and the public at large. The objective of this study was to determine the optimum resolution for prediction of corn grain yield using indirect sensor measurements. Corn rows, 15–30 m long, were randomly selected at three locations where the exact location of each plant was determined. In 2005 and 2006, four of eight rows at each location were fertilized with 150 kg N ha^{-1} as urea ammonium nitrate (28% N). A GreenSeeker^{TM} optical sensor was used to determine average Normalized Difference Vegetation Index (NDVI) across a range of plants and over fixed distances (20, 40, 45.7, 60, 80, 91.4, 100, 120, 140, 160, 180, 200, 220, and 240 cm). Individual corn plants were harvested and grain yield was determined. Correlation of corn grain yield versus NDVI was evaluated over both increasing distances and increasing number of corn plants. Then, the squared correlation coefficients (r_{cc}^2) from each plot (used as data) were fitted to a linear plateau model for each resolution treatment (fixed distance and number of corn plants). The linear-plateau model coefficient of determination (r_{lp}^2) was maximized when averaged over every four plants in 2004 and 2006, and over 11 plants in 2005. Likewise, r_{lp}^2 was maximized at a fixed distance of 95, 141, and 87 cm in 2004, 2005, and 2006, respectively. Averaged over sites and years, results from this study suggest that in order to treat spatial variability at the correct scale, the linear fixed distances should likely be $<$87 cm or $<$4 plants as an optimum resolution for detecting early-season differences in yield potential and making management decisions based on this resolution.

Keywords: corn; resolution; nitrogen; Normalized Difference Vegetation Index (NDVI); correlation coefficient; coefficient of determination

Introduction

In 2003, farmers in the United States grew 38% (US Grain Council 2003) of the world's corn (FAO [Food and Agriculture Organization of the United Nations] 2004). Corn, being one of the most important crops used by man, should be produced efficiently to supply the needs of the world's increasing population, which is projected to reach 7.5 billion by 2020 (FAO 2004). One of the inputs that needs to be better managed to

*Corresponding author. Email: bill.raun@okstate.edu

ISSN 0365-0340 print/ISSN 1476-3567 online

DOI: 10.1080/03650340802219979
http://www.informaworld.com

increase efficiency and reduce the risk to the environment is nitrogen (N), which is the main nutrient needed for growth and development of plant tissues and yield (Chung et al. 1999; Washmon et al. 2002).

Farmers often apply large amounts of N fertilizer to avoid deficiencies. In the entire world, about 85.0 million metric tons of N fertilizer was consumed in 2002 (FAO 2002), and 84.0 million metric tons of N in 2005 (FAO 2005). Of this, approximately 60% of the total is applied for cereal production. Some 67% of the N fertilizer applied for cereal production is lost (Raun and Johnson 1999) which leads to increased production costs, increased environmental and human risk (Sharpe et al. 1988), and poor N use efficiency (NUE) (Sowers et al. 1994). Many researchers reported that excessive preplant fertilizer N application has resulted in loss of N through several routes including immobilization, volatilization, leaching, and denitirification, significantly affecting NUE (Olson and Shallow 1984; Lutcher and Mahler 1988; Fowler and Brydon 1989; Wuest and Cassman 1992; Welch et al. 1996). Similarly, under N fertilization resulted in lower corn yields (Derby et al. 2004). However, application of N fertilizer as per the corn crop requirement in specific areas within a field resulted in increased yield and decreased contamination (Dinnes et al. 2002; Doerge 2002).

Huggins and Pan (1993) noted that among the benefits of increasing NUE are decreasing environmental degradation and human risk, and increasing profit in crop production by reducing N fertilizer input. Researchers are developing N management strategies that can replace or augment the conventional method of N fertilization. Remote sensing, which is a low cost, non-destructive, light reflectance-based technology (Mulla and Schepers 1997) can be used to estimate the N status of growing crops in the field during the growing season (Osborne et al. 2002).

Light reflectance near 550 nm (green) can be used to monitor N deficiencies of corn (Blackmer et al. 1994). Blackmer et al. (1996) found that N treatments in irrigated corn canopies could be easily discriminated in the 550–900 nm band. Stone et al. (1996), on the other hand, reported that the total N of winter wheat plants could be evaluated between 671 nm and 780 nm wavelengths. Remote sensing has been used to evaluate other nutrient deficiencies such as P concentrations of soybean [*Glycine max* (L.) Merr.] (Milton et al. 1991), S, Mg, K, P and Ca of corn leaves (Al-Abbas et al. 1974), Fe, S, Mg, and Mn in corn, wheat, barley (*Hordeum vulgare* L.), and sunflower (*Helianthus annuus* L.) (Masoni et al. 1996) and P uptake of bermudagrass [*Cynodon dactylon* (L.) Pers.] (Sembiring et al. 1998). Reflectance, the ratio of incoming to reflected radiance, can be used to estimate total N and chlorophyll content of fresh plant samples (Yoder and Pettigrew-Crosby 1995). Raun et al. (2001) showed that mid-season sensor reflectance measurements could be used to predict yield potential of winter wheat (measured between Feekes growth stages 4 and 6). One of the commonly used reflectance indices, the Normalized Difference Vegetation Index (NDVI) which is the ratio of red and near infrared reflectance (Knipling 1970) has been well researched for site-specific N management in several crops including corn (Lukina et al. 2001; Raun et al. 2002; Hong et al. 2006; Martin et al. 2007).

It is important to determine at which scale to sense and treat the variation existing in the field that will result in a more precise yield prediction and improved NUE. Raun et al. (1998) noted that misapplication for a specific field element size identified (where yield potential differences exist) could pose a risk to the environment and revenues. In wheat, Solie et al. (1996) stated that the optimum field element size provides the most precise measure of the available nutrient where the level of that nutrient changes with distance. They suggested that the field element size should have an 80–140 cm range.

Nitrogen deficiency of wheat (*Triticum aestivum* L.) and bermudagrass (*Cynodon dactylon* L.) was found to occur in areas less than 100 × 100 cm (Stone et al. 1996). Moreover, Solie et al. (1996) suggested that N fertilizer needs to be placed in each 150 × 150 cm area. In corn, few studies have attempted to assess the optimum resolution of N management using optical sensing techniques. Using a remotely sensed vegetation index, Zhang et al. (1999) found that a 9–12 m resolution optimized r^2 between NDVI and corn grain yield. The resolution set by Zhang et al. (1999) tended to ignore variability that can occur among plants in a small area. Past research showed that plant-to-plant variability in corn grain yield can be expected and averaged more than 2765 kg ha^{-1} over sites and years (Martin et al. 2005). To date, there is no research work on potential yield prediction of corn using different resolutions. Therefore, this study was designed to accurately determine the resolution where grain yield potential of corn could be predicted. The objective of this study was to determine the optimum resolution for predicting corn grain yield using optical sensor measurements.

Materials and methods

Three locations in Oklahoma were used for a three-year (2004–2006) study. The sites included Efaw near Stillwater (Norge silt loam: fine silty, mixed, active, thermic Udic Paleustolls), Lake Carl Blackwell (Pulaski fine sandy loam: coarse-loamy, mixed, superactive, non-acid, thermic, Udic Ustifluvent) and Hennessey (Shellabarger fine sandy loam: fine-loamy, mixed, superacitve, mesic, thermic Udic Argiustoll), Oklahoma. Composite soil samples were taken from the entire site, 0–15 cm deep, air-dried, processed and analyzed for pH, NH_4-N, NO_3-N, phosphorus and potassium, and reported in Table 1. The Lake Carl Blackwell site has been irrigated since 2004. The Efaw site is rainfed with custom made supplemental irrigation when rainfall was not available for extended periods while the Hennessey site was purely rainfed where rainfall is generally the limiting factor for optimum corn growth. Due to this limitation, the experiment was conducted at this site only in 2004. The experimental plots were conventionally tilled in the fall and harrowed before planting in early spring. The corn hybrid '33B51' (Pioneer Hi-Bred International Inc., Johnston, IA, USA) was planted at all sites in late March or early April using a John Deere 'MaxEmerge' planter. Plant populations were 79,000 plants ha^{-1}at Lake Carl Blackwell and 54,000 plants ha^{-1} at Efaw and Hennessey.

In 2004, four rows, 30 m in length were randomly selected at each of the three locations. In 2005 and 2006, eight rows, 15 m in length were selected at Efaw and Lake Carl Blackwell. Four of the eight rows were fertilized at the V6 growth stage with 150 kg N ha^{-1} as urea ammonium nitrate (28% N) while the other half received no fertilizer.

Table 1. Soil chemical properties determined prior to experiment from initial surface soil samples (0–15 cm) at three locations, Oklahoma, USA.

Site	pH	NH_4-N	NO_3-N	P	K
		mg kg^{-1}			
Efaw	5.9	13.9	3.7	20	90
LCB	5.6	28.4	4.4	45	144
Hennessey	4.8	24	5	100	–

LCB: Lake Carl Blackwell pH - 1:1 soil:water; K and P - Mehlich III; NH_4-N and NO_3-N - 2M KCl≠critical plant number exceeded data boundary.

The distance from the beginning of the row to the center of each plant was measured and recorded along with the row number and plant number for identification. The area that each plant occupied was determined by knowing the distance to and from its nearest neighbor (Equation (1), Martin et al 2005).

$$\text{Area (cm}^2) = \text{R} * [(0.5 * \text{AB}) + (0.5 * \text{BC})] \tag{1}$$

where: A is the plant before the plant in question; B is the plant in question; C is the plant following the plant in question; AB is the distance from A to B in cm; BC is the distance from B to C in cm; and R is fixed row spacing in cm.

Normalized difference vegetation index measurements were collected using a GreenSeeker^{TM} Optical Sensor Unit (NTech Industries, Inc.). However, for this research, the sensor was developed to collect NDVI as a function of distance with a conventional bicycle as the building framework. An adjustable pole was installed on the bicycle that extended vertically up to 200 cm. The sensor was installed on a horizontal bar protruding 38.1 cm from the adjustable pole (Figure 1). The sensor height, which was adjustable, was held constant at 92 cm from the top of the crop canopy when measuring NDVI in each row (Figure 1). A shaft encoder installed on the back tire of the bicycle was used to collect a consistent number of pulses for each revolution of the wheel. This allowed calculating the distance traveled between each pulse and determine the exact position of each sensor reading.

When the sensor began to measure NDVI with distance, a dull white cardboard strip was placed on the ground at the exact beginning and end of each row. The NDVI value measured by the sensor when it looked at this cardboard was close to ‘0’. The NDVI values over the soil surface or plant material were all greater than 0.20. Thus, the dull

Figure 1. Framework for the bicycle and the adjustable pole that holds the sensor parallel and directly above the corn row. The shaft encoder is used to determine the distance at which NDVI is recorded is shown on the rear tyre of the bicycle.

white cardboard strip was used to identify the exact beginning and ending point in each row. Subsequently, NDVI measurements were averaged for each plant using half the distance to and from the neighboring plants within the row as described in Equation (1).

Normalized Difference Vegetation Index was measured over pre-determined distances of 20 (0.66), 40 (1.31), 45.7 (1), 60 (1.97), 80 (2.63), 91.4 (3), 100 (3.28), 120 (3.97), 140 (4.59), 160 (5.25), 180 (5.91), 200 (6.56), and 240 (7.87) cm (ft) within each row (Table 2). Simultaneously, the number of corn plants within the set distances was recorded. The number of corn plants and distances measured were used to determine the resolution required for treating spatial variability, and to estimate yield potential.

At physiological maturity of corn, each plant was cut just above the soil surface and weighed. Then, the ear from each plant was shucked and weighed. The wet ears and stalks were dried in a forced air oven at 66°C for 48 h and passed through a hand turned 'NeverFail' (Root-Health MFG. CO., Plymouth, USA) corn sheller. The grain from each ear was weighed for dry weight to calculate grain yield. Preliminary data analysis was performed using SAS (SAS 2003) statistical software. Normalized Difference Vegetation Index recorded over each of the fixed distances and the number of corn plants within the set distances was plotted against corresponding grain yield of each row ($n = 24$ for each plot). Then r_{cc}^2 from each plot (used as data) were fitted to a linear plateau model (Nelson

Table 2. Planting dates, harvest dates, and growth stages for resolution determination study at Efaw, Hennessey and Lake Carl Blackwell, OK, USA, from 2004–2006.

Location	Growth Stage	Planting Date	Sensing Date	Harvest Date
2004				
Efaw	V8	7/4/04	26/5/04	25/8/04
Hennessy	V8	27/4/04	16/6/04	13/9/04
LCB	V8	3/4/04	28/5/04	2/8/04
2005				
Efaw	V6	7/4/05	19/5/05	1/8/05 (rows 1–3) 26/8/05 (rows 4–8)
LCB	V6	12/4/05	23/5/05	8/9/05 (rows 1–2) 20/9/05 (rows 3–8)
Efaw	V8	7/4/05	27/5/05	1/8/05 (rows 1–3) 26/8/05 (rows 4–8)
LCB	V8	12/4/05	27/5/05	8/9/05 (rows 1–2) 20/9/05 (rows 3–8)
Efaw	V10	7/4/05	2/6/05	1/8/05 (rows 1–3) 26/8/05 (rows 4–8)
LCB	V10	12/4/05	2/6/05	8/9/05 (rows 1–2) 20/9/05 (rows 3–8)
2006				
Efaw	V6	30/3/06	19/5/06	24/8/06
LCB	V6	31/3/06 (rows 5–8) 11/4/06 (rows 1–4)	22/5/06 (rows 1–4) 17/5/06 (rows 5–8)	14/8/06
Efaw	V8	30/3/06	24/5/06	24/8/06
LCB	V8	31/3/06 (rows 5–8) 11/4/06 (rows 1–4)	29/5/06 (rows 1–4) 22/5/06 (rows 5–8)	14/8/06
Efaw	V10	30/3/06	2/6/06	24/8/06
LCB	V10	31/3/06 (rows 5–8) 11/4/06 (rows 1–4)	5/6/06 (rows 1–4) 29/5/06 (rows 5–8)	14/8/06 14/8/06

et al. 1985) for each resolution treatment (fixed distance and number of corn plants) using the non-linear (NLIN) procedure in SAS. The linear plateau model was:

$$\mathrm{Y} = \beta_0 + \beta_1 \mathrm{X} \quad \text{if } \mathrm{X} < \mathrm{X}_0 [2]$$
$$\mathrm{Y} = p \quad \text{if } \mathrm{X} > \mathrm{X}_0 [3]$$

where: Y is r_{cc}^2, β_0 is the intercept (r_{cc}^2 when X = 0); β_1 is the coefficient of the linear plateau phase of the model; X is the number of corn plants or fixed distance (cm); X_0 denotes the critical number of corn plants or fixed distance at which the maximum r_{cc}^2 was achieved (p).

Results and discussion

The variation in optimum resolution determined from the number of corn plants was very high across years, locations and corn growth stages. The linear-plateau model (the number of corn plants as a predictor) captured a significant ($p < 0.05$) portion of the variability in r_{cc}^2s (dependent variable) for most (85%) of the year-location-stage models with r_{lp}^2 values ranging 0.40–0.95 (Table 3). Some 62% of the year-location-stage models had $r_{lp}^2 \geq 0.65$.

Averaged over years, locations and stages, the number of corn plants where r_{lp}^2 values were maximized (NDVI versus yield) was every 7 plants (Table 3). The median value (6-plant) was also close to the average. It is important to note that the range in the number of plants that represented the optimum resolution was wide (from 2–15 plants), suggesting a highly variable joint (critical number of corn plants) using the r_{cc}^2 data.

In 2004, a higher resolution (four plants) was observed (small number of plants) when averaged over locations. The lowest resolution was five plants while the highest resolution was two plants. In this year, measurements were taken only at the V8 corn growth stage at the three locations (Table 3). The difference in the number of corn plants set as critical (the joint of each model) for this year were not different partly attributed to collecting data only at one stage. A lower resolution was obtained in 2005 (7–15 plants) with an average of 11 plants. In general, results from 2004 and 2006 were lower, averaging four plants. The best resolution was two plants while the worst was six plants, less than the smallest resolution of seven plants in 2005. It could be that the resolution where yield potential could best be predicted when stress was less, and more plants were present (2005), whereas less plants when increased stress was present (2004 and 2006). The differences between individual plants will likely be exacerbated when moisture stress occurs, and less pronounced under non-limiting conditions, possibly explaining these results.

A closer examination of the joint by year, location and corn growth stage showed that in 2005 at Efaw a higher resolution was obtained for r_{cc}^2s derived from NDVI measurements taken at V6 growth stage while at the V8 and V10 growth stages a relatively lower resolution was determined from each model. In 2006, almost the same resolution (2–2.5 plants) was determined across growth stages although the resolution was slightly lower at V10. At Lake Carl Blackwell at V6 in 2005 and at V8 in 2006, the linear-plateau model failed to converge. For the other stages, resolution did not change as the growth stages in which the r_{cc}^2 of NDVI measurements were taken progressed. In general, the variability of the resolution determined using corn plants in a row was more pronounced across years and locations but not growth stages. This suggests that the number of corn plants that could theoretically be used for making management decisions based on yield potential could be implemented between V8 to V10 corn growth stages. Linear-plateau models were best when fitted for each year and location. It should however, be noted that management

Table 3. Linear-plateau model with critical number of corn plants (joint) and coefficient of determination (r_{lp}^2) derived from the correlation between NDVI and corn grain yield versus number of corn plants at three growth stages at Efaw, Hennessey and Lake Carl Blackwell, 2004–2006.

Year	Location	Growth Stage	Joint¶	Model	r_{lp}^2
2004	Efaw	V8	5	Y = 0.0557 + 0.0325x, when X < 5; Y = 0.22, when X > 5**	0.67
	Lake Carl Blackwell	V8	2	Y = −0.0267 + 0.169x, when X < 2; Y = 0.55, when X > 2	0.30
	Hennessey	V8	4	Y = 0.015 + 0.1499x, when X < 3.5; Y = 0.51, when X > 3.5*	0.47
2005	Efaw	V6	7	Y = 0.0333 + 0.027x, when X < 7.2; Y = 0.23, when X > 7.2***	0.83
	Lake Carl Blackwell	V6		≠	
	Efaw	V8	10	Y = 0.0709 + 0.0447x, when X < 9.5; Y = 0.49, when X > 9.5***	0.86
	Lake Carl Blackwell	V8	15	Y = −0.00024 + 0.01341x, when X < 15.3; Y = 0.2, when X > 15.3***	0.96
	Efaw	V10	9	Y = 0.0799 + 0.0395x, when X < 9; Y = 0.44, when X > 9***	0.83
	Lake Carl Blackwell	V10	15	Y = 0.0055 + 0.0135x, when X > 14.7; Y = 0.2, when X < 14.7***	0.95
2006	Efaw	V6	2	Y = 0.1921 + 0.069x, when X > 2; Y = 0.33, when X < 2	0.22
	Lake Carl Blackwell	V6	6	Y = −0.00787 + 0.0099x, when X > 6; Y = 0.05, when X < 6*	0.47
	Efaw	V8	2	Y = 0.1975 + 0.0989x, when X < 2; Y = 0.4, when X < 2*	0.40
	Lake Carl Blackwell	V8		≠	
	Efaw	V10	2	Y = 0.0943 + 0.1498x, when X > 2.5; Y = 0.47, when X < 25***	0.71
	Lake Carl Blackwell	V10	6	Y = 0.0205 + 0.0169x, when X > 6.2; Y = 0.13, when X < 6.2**	0.65

*, ** and *** model significant at the 0.05, 0.01, and 0.001 levels of probability, respectively. ≠ Critical plant number exceeded data boundary. ¶ Critical point (number of corn plants) determined by defining the linear and plateau phases of the model separately.

decisions at resolutions greater than 15 plants will likely ignore detectable differences in grain yield. In general, when plant populations were low, the resolution at which yield potential was best recognized included less plants, especially at early stages of growth. Alternatively, when plant populations were high, the resolution where yield potential could be best predicted required more plants.

The use of distance to determine resolution was better than when using the number of corn plants when looking at the r_{lp}^2 (0.5–0.95) in Table 4 (except Lake Carl Blackwell in 2006 at V6). The coefficient of determination would have improved at Lake Carl Blackwell if a linear model instead of linear-plateau model was used although it is impossible to delineate a critical resolution distance with the use of a linear model. Averaged over the three years, all locations and growth stages, a distance of 110 cm was determined as the optimum resolution. The highest resolution was 66 cm (in 2006 at Efaw at the V8 and V10 growth stages) while the lowest resolution was 171 cm (at Lake Carl Blackwell in 2005 at the V8 growth stage) with a range of 105 cm. Across years, 95, 141 and 87 cm were set as the optimum resolutions in 2004, 2005 and 2006, respectively. Across locations, resolution distance was 107, 100 and 115 cm at Efaw, Hennessey and Lake Carl Blackwell, respectively. In both 2005 and 2006 at Efaw, resolution decreased as NDVI measurements progressed from the V6 to V10 growth stages. A similar trend was observed in 2005 at Lake Carl Blackwell. At this site in 2006, no trend was observed although the resolution at V6 was higher than the resolution at V8 and V10 (Table 4). The coefficient of determination at Efaw was maximized at the V8 growth stage in 2005 and at the V6 growth stage in 2006.

The optimum resolution was variable in each year suggesting that this too was influenced by temporal variability, and how temporal qualities influence growth. The r_{lp}^2 of each linear-plateau model in each of the two approaches used to determine optimum resolution revealed that the fixed distance approach would be better. However, with all ranges of resolutions (i.e. high, medium or low), the number of corn plants and the distance generally coincided based on average distance from neighboring corn plants. Martin et al. (2005) established a critical sensing distance of 50 cm or less for treating factors that affect corn yield. Compared with his results, we found a lower resolution distance in all models (the best resolution was 66 cm, at Efaw in 2006 at both V6 and V8). Compared to a 900–1200 m spatial resolution recommended by Zhang et al. (1999) based on r^2, the distance we set can be considered as high resolution.

The wide variation in optimum resolution at the Lake Carl Blackwell site in 2005 and 2006 could be due to differences in the planting dates. The planting dates for four of the eight rows on the south-east side in 2005 and on the west side in 2006 were April 11 and March 31, respectively. Alternatively, planting dates for the other four rows on the north-west side in 2005 and east side in 2006 were April 18 and 11, respectively. This delay, given the warm temperature in both years since late March, means active growth of corn and can influence the resolution at which yield potential is recognized. Some of the differences in the optimum resolution within a season and across locations could be due to plant biomass. In addition, post-sensing plant stress (such as drought, high temperatures, nutrient deficiency, insect damage, hail damage, poor pollination, and animal damage) can result in a poor relationship between grain yield and NDVI in the linear-plateau model resulting in a poor r_{lp}^2. Uneven emergence was reported as a possible cause of increased or decreased grain yield when soils were dry at the time of planting (Nafziger et al. 1991). In 2006, severe heat stress was encountered throughout the growing season at all sites. This severe heat had daily maximums that exceeded 38°C from mid-July to early August in 2006 at Lake Carl Blackwell and Efaw.

Table 4. Linear-plateau model with critical fixed distance resolution (joint) and coefficient of determination (r_{lp}^2) derived from the correlation between NDVI and corn grain yield versus fixed distance at three growth stages at Efaw, Hennessey and Lake Carl Blackwell, OK, USA, from 2004–2006.

Year	Location	Growth Stage	Joint[¶]	Model	r_{lp}^2
2004	Efaw	V8	93	$Y = -0.063 + 0.0043x$, when $X < 93.4$; $Y = 0.33$, when $X > 93.4$***	0.95
2004	Lake Carl Blackwell	V8	92	$Y = 0.0729 + 0.0026x$, when $X < 92$; $Y = 0.31$, when $X > 92$***	0.66
2004	Hennessey	V8	100	$Y = -0.0698 + 0.0033x$, when $X < 100$; $Y = 0.26$, when $X > 100$**	0.61
2005	Efaw	V6		≠	
2005	Lake Carl Blackwell	V6	140	$Y = -0.0077 + 0.0007x$, when $X < 140$; $Y = 0.09$, when $X > 140$**	0.63
2005	Efaw	V8	171	$Y = -0.0146 + 0.0024x$, when $X < 171.1$; $Y = 0.39$, when $X > 171.1$***	0.90
2005	Lake Carl Blackwell	V8	133	$Y = -0.0093 + 0.0007x$, when $X < 132.9$; $Y = 0.09$, when $X > 132.9$***	0.70
2005	Efaw	V10	156	$Y = 0.0212 + 0.002x$, when $X < 156.4$; $Y = 0.34$, when $X > 156.4$***	0.95
2005	Lake Carl Blackwell	V10	106	$Y = -0.0094 + 0.0011x$, when $X > 106.2$; $Y = 0.11$, when $X < 106.2$***	0.72
2006	Efaw	V6	92	$Y = 0.1573 + 0.0027x$, when $X > 92.5$; $Y = 0.41$, when $X < 92.4$***	0.75
2006	Lake Carl Blackwell	V6	100	$Y = 0.0014 + 0.00001x$, when $X > 100$; $Y = 0.01$, when $X < 100$	0.15
2006	Efaw	V8	66	$Y = 0.1158 + 0.0049x$, when $X < 66.1$; $Y = 0.44$, when $X < 66.1$***	0.94
2006	Lake Carl Blackwell	V8		≠	
2006	Efaw	V10	66	$Y = 0.0677 + 0.006x$, when $X > 65.9$; $Y = 0.47$, when $X < 65.9$***	0.87
2006	Lake Carl Blackwell	V10	111	$Y = 0.0887 + 0.0019x$, when $X > 110.6$; $Y = 0.29$, when $X < 110.6$***	0.71

*, ** and *** model significant at the 0.05, 0.01, and 0.001 levels of probability, respectively. ≠ Critical plant number exceeded data boundary. ¶ Critical point (distance in cm) determined by defining the linear and plateau phases of the model separately.

Conclusions

The use of distance to determine resolution was better than when using specific numbers of corn plants when looking at the r_{lp}^2. Looking at the linear-plateau models generated from the r_{lp}^2s (grain yield versus NDVI for different numbers of corn plants), the resolution where yield differences were best recognized was when averaged over every four plants in 2004 and 2006 and over 11 plants in 2005. Likewise, the r_{lp}^2 was maximized at a fixed distance of 95, 141, and 87 cm in 2004, 2005 and 2006, respectively. Identifying the optimum resolution where spatial variability should be treated is a complicated task. Averaged over sites and years, this study suggests that in order to treat spatial variability at the correct scale, the linear fixed distances should likely be <87 cm or <4 plants as an optimum resolution for detecting early-season differences in yield potential and making management decisions based on this resolution.

References

Al-Abbas AH, Barr R, Hall JD, Crane FL, Baumgardner MF. 1974. Spectra of normal and nutrient-deficient maize leaves. Agron J. 66:16–20.

Blackmer TM, Schepers JS, Varvel GE. 1994. Light reflectance compared with other nitrogen stress measurement in corn leaves. Agron J. 86:934–938.

Blackmer TM, Schepers JS, Varvel GE, Walter-Shea EA. 1996. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron J. 88:1–5.

Chung R, Chen H, Wu P. 1999. Effect of split applications of nitrogen fertilizer on the growth and nitrogen composition of Chinese mustard. Commun Soil Sci Plant Anal. 30:307–316.

Derby NE, Casey FXM, Knighton RE, Steels DD. 2004. Midseason nitrogen fertility management for corn based on weather and yield prediction. Agron J. 96:494–501.

Dinnes DL, Karlen DL, Jayne DB, Kaspar TC, Hatfield JL, Colvin TS, Cambardella CA. 2002. Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agron J. 94:153–171.

Doerge TA. 2002. Variable-rate nitrogen management creates opportunities and challenges for corn producers. Des Moines (IA): Plant Management Network. [Accessed 11 November 2007] Available from: http://www.plantmanagementnetwork.org/cm/ Crop Management doi. 10. 10/94/CM-2002-0905-01-RS.

FAO (Food and Agriculture Organization of the United Nations). 2002. STAT Data. Rome, Italy: FAO. [Accessed 20 October 2007] Available from: http://faostat.fao.org

FAO (Food and Agriculture Organization of the United Nations). 2004. STAT Data. Rome, Italy: FAO. [Accessed 30 September 2007] Available from: http://faostat.fao.org

FAO (Food and Agriculture Organization of the United Nations). 2005. STAT Data. Rome, Italy: FAO. [Accessed 13 October 2007] Available from: http://faostat.fao.org

Fowler DB, Brydon J. 1989. No-till winter wheat production on the Canadian Prairies: Timing of nitrogen fertilization. Agron J. 81:817–825.

Hong N, White JG, Weisz R, Crozier CR, Gumpertz ML, Cassel DK. 2006. Remote sensing-informed variable-rate nitrogen management of wheat and corn: agronomic and groundwater outcomes. Agron J. 98:327–338.

Huggins DR, Pan WL. 1993. Nitrogen efficiency component analysis: an evaluation of cropping system differences in productivity. Agron J. 85:898–905.

Knipling EB. 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sens Environ. 1:155–159.

Lukina EV, Freeman KW, Wynn KJ, Thomason WE, Mullen RW, Klatt AR, Johnson GV, Elliott RL, Stone ML, Solie JB, RaunWR. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J Plant Nutr. 24:885–898.

Lutcher EV, Mahler RL. 1988. Sources and timing of spring topdress nitrogen on winter wheat in Idaho. Agron J. 80:648–654.

Martin KL, Girma K, Freeman KW, Teal RK, Tubaña B, Arnall DB, Chung B, Walsh O, Solie JB, Stone ML, Raun WR. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron J. 99:384–389.

Martin KL, Hodgen PJ, Freeman KW, Melchiori R, Arnall DB, Teal RK, Mullen RW, Desta K, Phillips SB, Solie JB, Stone ML, Caviglia O, Solari F, Bianchini A, Francis DD, Schepers JS, Hatfield J, Raun WR. 2005. Plant-to-plant variability in corn production. Agron J. 97:1603–1611.
Masoni A, Ercoli L, Mariotti M. 1996. Spectral properties of leaves deficient in iron, sulfur, magnesium, and manganese. Agron J. 88:937–943.
Milton NM, Eisweth BA, Ager CM. 1991. Effect of phosphorus deficiency on spectral reflectance and morphology of soybean plants. Remote Sens Environ. 36:121–127.
Mulla DJ, Schepers JS. 1997. Key processes and properties for site-specific soil and crop management. In: Pierce FJ, Sadler EJ, editors. The site-specific management for agricultural systems. Madison (WI): ASA, CSSA, and SSSA. p. 1–18.
Nafziger ED, Carter PR, Graham EE. 1991. Response of corn to uneven emergence. Crop Sci. 31:811–815.
Nelson LA, Voss RD, Pesek JT. 1985. Agronomic and statistical evaluation of fertilizer response. In: Angelstad OP, editor. Fertilizer technology and use. 3rd ed. Madison (WI): ASA. p. 53–90.
Olson RV, Shallow CW. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci Soc Am J. 48:583–586.
Osborne SL, Schepers JS, Francis DD, MR Schlemmer. 2002. Detection of phosphorus and nitrogen deficiencies in corn using spectral radiance measurements. Agron J. 94:1215–1221.
Raun WR, Johnson GV. 1999. Improving nitrogen use efficiency for cereal production. Agron J. 91:357–363.
Raun WR, Solie JB, Johnson GV, Stone ML, Lukina EV, Thomason WE, Schepers JS. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron J. 93:131–138.
Raun WR, Solie JB, Johnson GV, Stone ML, Mullen RW, Freeman KW, Thomason WE, Lukina EV. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron J. 94:815–820.
Raun WR, Solie JB, Johnson GV, Stone ML, Whitney RW, Lees HL, Sembiring H, Phillips SB. 1998. Micro-variability in soil test, plant nutrient and yield parameter. Soil Sci Soc Am J. 62:683–690.
SAS Institute. 2003. SAS/STAT user's guide. Release 6.03 ed. Cary (NC): SAS Inst.
Sembiring H, Raun WR, Johnson GV, Stone ML, Solie JB, Phillips SB. 1998. Detection of nitrogen and phosphorus nutrient status in bermudagrass using spectral radiance. J Plant Nutr. 21:1189–1206.
Sharpe RR, Harper LA, Giddens JE, Langdale GW. 1988. Nitrogen use efficiency and nitrogen budget for conservation tilled wheat. Soil Sci Soc Am J. 52:1394–1398.
Solie JB, Raun WR, Whitney RW, Stone ML, Ringer JD. 1996. Optical sensor based field element size and sensing strategy for nitrogen application. Trans ASAE. 39:1983–1992.
Sowers KE, Pan WL, Miller BC, Smith JL. 1994. Nitrogen use efficiency of split nitrogen applications in soft white winter wheat. Agron J. 86:942–948.
Stone ML, Soile JB, Raun WR, Whitney RW, Taylor SL, Ringer JD. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans ASAE. 39:1623–1631.
United States Grain Council. 2003. World corn production and trade. Washington, DC, US: Grains Council. [Accessed 28 September 2007] Available from: http://www.grains.org/grains/corn.html
Washmon CN, Solie JB, Raun WR, Itenfisu DD. 2002. Within field variability in wheat at grain yield over nine years in Oklahoma. J Plant Nutr. 25:2655–2662.
Welch LF, Johnson PE, Pendleton JW, Miller LB. 1996. Efficiency of fall-vs. spring-applied nitrogen for winter wheat. Agron J. 58:271–274.
Wuest SB, Cassman KG. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. Uptake efficiency of preplant versus late-season applied N. Agron J. 84:682–688.
Yoder BJ, Pettigrew-Crosby RE. 1995. Predicting nitrogen and chlorophyll content and concentrations from reflectance spectra (400–2500 nm) at leaf and canopy scales. Remote Sens Environ. 53:199–211.
Zhang M, O'Neill M, Hendley P, Drost D, Ustin S. 1999. Corn and soybean yield indicators using remotely sensed vegetation index. Paper presented at: 3rd Annual Precision Agriculture Conference; November 18–19, 1999. Brandon, MB USA: Assiniboine College.