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Growth Stage, Development, and Spatial Variability in Corn Evaluated Using Optical Sensor Readings*

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ABSTRACT

Knowing the exact stage of growth where expressed plant variability is at a maximum might lead to the identification of times when in-season fertilization could have the greatest impact. One field experiment was initiated to measure daily plant growth and spatial variability in corn (*Zea mays* L.) over the entire growth cycle using optical sensor readings (normalized difference vegetative index, or NDVI) collected every 0.05 m in length, 0.6 m wide from 4 corn rows, 27 m in length. Averaged over all 4 rows, plants were spaced 21 ± 7 cm apart. For each row and sensing date, the mean, standard deviation, and coefficient of variation (CV) were computed from the NDVI readings. Eighteen days after planting, NDVI values were near 0.20, and later peaked near 0.81, 54 days after planting at the 10-leaf growth stage (V10). Coefficients of variation were found to peak much earlier, 33 to 35 days after planting at the 6-leaf growth stage (V6), (31% to 34% during this period). Expressed spatial variability decreased from >30% at V6 to just under 10% at the 11-leaf growth stage (V11). Immediately following V11, a distinct increase in CVs was found just following the initiation of tasseling (VT), but lasted for only 2 days. Expressed spatial variability was greatest at the V6 growth stage, and this peak in the within-row-by-plant variability may be the precise growth stage at which treating that variability will have the greatest impact.

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INTRODUCTION

Precision agriculture is a term commonly employed today that to some extent implies more "precise" application of nutrients and/or pesticides. However, temporal influence on expressed variability, and the exact resolution (scale dependent) where precision agricultural technologies should operate has not been agreed upon. To some, precision agriculture might imply grid soil sampling on 0.5 ha grids, while to others it might mean collecting yield monitor and/or satellite data on a 30 m resolution. In corn (*Zea mays* L.), the issue of resolution becomes increasingly important as sensor strategies to manage by-plant variability on the go are now available.

The time of sensing is critical to determining potential yield of the crop. Raun et al. (1986) showed that corn seedlings that emerge late essentially become weeds competing for moisture and nutrients, with almost no chance of reproductive development. Late germination can result in competitor plants that reduce yield. Sensing late germination, the products of which are expressed in a smaller plant, could be very important for mid-season nitrogen (N) management. Late emergence within a competitive stand will almost assuredly lead to decreased yield potential, and as a result, mid-season N fertilization should be adjusted accordingly.

Extensively distributed information on how corn plants develop has been available from Iowa State University (1993). The following discussion comes from its site as it relates to early-season detection of yield potential. At the 6-leaf vegetative stage (V6) the growing point and tassel are above the soil surface and the stalk is beginning a period of increased elongation. By the 9-leaf stage (V9) an ear shoot (potential ear) will develop from every above-ground node, except the last 6–8 nodes below the tassel. Initially, each ear shoot develops faster than the ear shoots originating above it on the stalk. However, growth of most lower-stalk ear shoots eventually slows, and only the upper one or two ear shoots ever develop into a harvestable ear. The tassel begins to develop rapidly and the stalk continues rapid elongation. Although the ear shoots (potential ears) were formed just before tassel formation (V5), the number of ovules (potential kernels) on each ear and the size of the ear are determined by the 12-leaf stage (V12). In this discussion, it is clear that even though much can be discerned concerning yield-potential at V6, waiting until V12 would provide a much clearer picture of potential grain yield.

While mid-season growth and development is important, planting date has always held critical yield defining information for corn. Swanson and Wilhelm (1996) reported that maximum yields were achieved by planting corn around May 10 (near Lincoln, NE) and that yields declined when planting was delayed beyond this time. The same trend (for late corn-planting dates to result in decreased grain yields) was shown by Dungan (1944), Ahmadi et al. (1993), and Mascagni and Boquet (1996).

Coefficients of variation (CV) were first employed as a relative measure of variation. The CV is defined as the standard deviation expressed as a percentage of the mean (Senders, 1958). Mills (1924) indicated that the CV is affected by the value of the mean, as well as by the size of the standard deviation. Coefficients of variation have been used to evaluate results from different experiments involving the same units of measure, possibly conducted by different persons (Steel et al., 1997). Little and Hills (1978) indicated that the variability among experimental units within experiments that have different units of measurements and/or plot sizes can be compared using CVs. Steel et al. (1997) stated that the CV is a relative measure of variation, in contrast to the standard deviation, which is measured in the same units as the observation.

The objectives of this study were (1) to evaluate daily changes in high-resolution sensor data collected from 4 corn rows over an entire cycle, and (2) to characterize expressed spatial variability as a function of physiological growth stage.

MATERIALS AND METHODS

Beginning August 12, 2002, optical sensor readings were collected from a hybrid corn trial planted near Texcoco, Mexico. Sensor readings were taken every 1–2 days from 4 rows, 27 m in length. Sensor readings started 18 days after planting (August 12, 2002) and ended 129 days after planting (December 4, 2002). The soil at this site is classified as a fine-silty, mixed, fluventic hapludoll. The corn hybrid CMS-939083 was planted on July 24, 2002, at a rate of 64,000 seeds ha^{-1} using 0.76 m row spacing. Immediately following emergence, distance of each plant from its neighbor (front and back) was recorded in each of the 4 rows (125 to 130 plants per row). For all 4 rows, the average distance between plants was 21 ± 7 cm, resulting in an established stand of 62,656 plants ha^{-1}.

A GreenSeeker$^{\text{TM}}$ hand held optical sensor unit (NTech Industries, Inc.) was used to collect normalized difference vegetative index (NDVI) measurements. This device uses a patented technique to measure crop reflectance and to calculate NDVI. The unit senses a 0.6 × 0.01 m spot when held at a distance of approximately 0.6–1.0 m from the illuminated surface. The sensed dimensions remain approximately constant over the height range of the sensor. The sensor unit has self-contained illumination in both the red [650 ± 10 nm full width half magnitude (FWHM)] and NIR (770 ± 15 nm FWHM) bands. The device measures the fraction of the emitted light in the sensed area that is returned to the sensor (reflectance). These fractions are used within the sensor to compute NDVI according to the following formula:

$$\text{NDVI} = \frac{F_{\text{NIR}} - F_{\text{Red}}}{F_{\text{NIR}} + F_{\text{Red}}}$$

Where: F_{NIR}—Fraction of emitted NIR radiation returned from the sensed area (reflectance). F_{Red}–Fraction of emitted red radiation returned from the sensed area (reflectance).

The sensor unit is designed to be hand held and measurements are taken as the sensor is passed over the crop surface. The sensor samples at a very high rate (approximately 1000 measurements per second) and averages measurements between outputs. The sensor outputs NDVI at a rate of 10 readings per second. The sensor was passed over the crop at a height of approximately 0.9 m above the crop canopy and oriented so that the 0.6 m sensed width was perpendicular to the row and centered over the row. With advancing stage of growth, sensor height above the ground increased proportionally. Travel velocities were at a slow walking speed of approximately 0.5 m/s resulting in NDVI readings averaged over distances of <0.05 m.

A total of 450 to 550 individual NDVI readings were recorded from each row for each date of sampling. The mean NDVI, standard deviation, and coefficient of variation (CV = [standard deviation/mean] *100) were computed for each row and date. At the end of the cycle, CV and mean NDVI values (retaining all the by-row information) were plotted as a function of time. Growth stages in corn were identified using the terminology developed at Iowa State University (1993).

On December 4, 2002, each corn plant was cut just above the soil and the entire plant (stalk, leaves, and ear) was weighed. A hard freeze (< -2.2°C f or 3 hours) occurred during the evenings of November 18 and 19, which reduced total plant and grain yields. Once whole plant weights were recorded, the ear from each plant was removed from the husks, and weighed independently.

RESULTS

Average NDVI values by row and date are plotted as a function of time in Figure 1. Average NDVI and CVs on the date when a physiological change in growth stage was recorded are reported in Table 1. When sensor readings were first made, 18 days after planting on August 12, 2002, NDVI values were below 0.20, and corn plants were in the V3 stage (uppermost 3rd leaf collar visible). Average NDVI values peaked at V10 (10th leaf collar visible), near 0.79, 59 days after planting. Soon after V10, NDVI values were somewhat stable until near VT, when immature tassels were first visible, 68 days after planting. Average NDVI values remained above 0.70 from V8 to R1 (45 to 72 days after planting). After VT, NDVI values declined steadily. A discontinuity in the NDVI curve was caused by the hard freeze in November.

The relationship between CV and date of NDVI sensor readings is plotted in Fig. 2. When readings were first collected, CVs were relatively low (14.3% on August 12). Average distance between plants was 21 ± 7 cm, and the leaves on

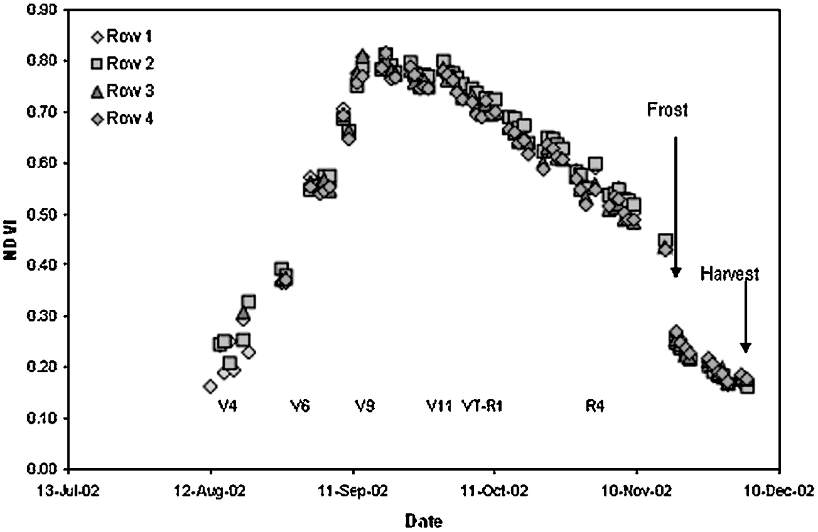

Figure 1. Average normalized difference vegetative index (NDVI) sensor readings collected from four corn rows, August to October, 2002, Texcoco, Mexico.

these V4 plants were not long enough to extend into the drip-line of neighboring plants. Surface coverage of the soil was approximately 20%. Fifteen days later, CVs peaked at 31%, corresponding with corn growth stage V6 (33 days after planting). At no other stage of growth were the differences in plant size so noticeable. At V6, corn leaves from neighboring plants touched, and soil coverage was estimated to be 45% to 50%. To some extent, the greatest variability should be detected when half of the sensed area includes soil because of the striking contrast in NDVI (<0.2 for soil and generally 0.3 to 0.9 for plant material).

After V6, the corn canopy began to close rapidly, with many leaves from adjacent plants intersecting one another. As this occurred, CV decreased back to 17.5% at corn growth stage V9 (48 days after planting), similar to where they started when readings were first initiated at V4. Soil coverage at V9 was visually estimated to be 75% to 80%. Just prior to tasseling (VT, 68 days after planting), CVs were at a minimum (9.1%) (Fig. 2, Table 1). At this growth stage, soil coverage by the canopy would be near maximum, with more uniform leaf color. At the onset of VT (68 days after planting), light yellow-green tassels began to appear in a heterogeneous fashion. A second peak in CV (first peak encountered at V6) was found just between the transition from VT to R1 (70 to 71 days after planting). A trend for the larger, darker green plants to have the first emerging tassels was noted. This was expressed in the increased CV following VT, and was detected in the NDVI optical sensor readings, known to be excellent predictors of plant biomass (Stone et al., 1996).

Table 1
Corn growth stages, corresponding dates, time intervals when sensor readings were collected, mean NDVI and CVs, Texcoco, Mexico, 2002

Growth stage	Date	Days from planting	NDVI	CV, %
Planting	July 24, 2002	0	0	0
V3	August 12, 2002	18	0.16	14.3
V4	August 15, 2002	21	0.22	18.0
V5	August 20, 2002	26	0.28	25.2
V6	August 27, 2002	33	0.38	31.0
V7	September 2, 2002	38	0.56	29.2
V8	September 9, 2002	45	0.70	24.4
V9	September 12, 2002	48	0.76	17.5
V10	September 23, 2002	59	0.79	10.2
V11	September 27, 2002	63	0.75	10.2
VT	October 2, 2002	68	0.77	9.1
R1	October 6, 2002	72	0.73	12.7
R2	October 14, 2002	80	0.68	11.4
R3	October 21, 2002	87	0.61	12.4
R4	November 1, 2002	97	0.57	14.8
—Frost—*	November 18, 2002	114	0.26	33.5
R5	November 28, 2002	124	0.19	37.1
Harvest	December 3, 2002	129	0.17	39.5

*2 consecutive days with evening frost accelerated senescence and physiological maturity.

NDVI—normalized difference vegetative index.

CV—cefficient of variation, %.

Beyond R1, CVs declined, reaching 12.4% at R3 just prior to the onset of rapid plant senescence. Following R3, CVs again increased and peaked at 39.5% the day prior to harvest. An early frost (3 continuous days with evening temperatures below 0°C) was encountered just beyond R3, which resulted in cell blasting and more rapid senescence. This was evident in the overnight increases in CVs and decreased NDVI (Fig. 2, Table 1).

For a small subset of the data, by-plant yield (entire plants, stalk + ear harvested at the base) over 6 m of row is plotted against corresponding NDVI sensor readings collected from exactly the same area at the 7 leaf and 10 leaf growth stages, 87 and 70 days earlier (Fig. 3). Although the sensor data were collected at a much higher frequency (roughly 4 sensor readings per plant, averaging 21 cm apart), it is apparent that as early as September 6 (7-leaf stage) these readings tracked final plant yield. This was also noted at the 10-leaf stage, but relative magnitudes of the sensor reading were much smaller once the canopy began to

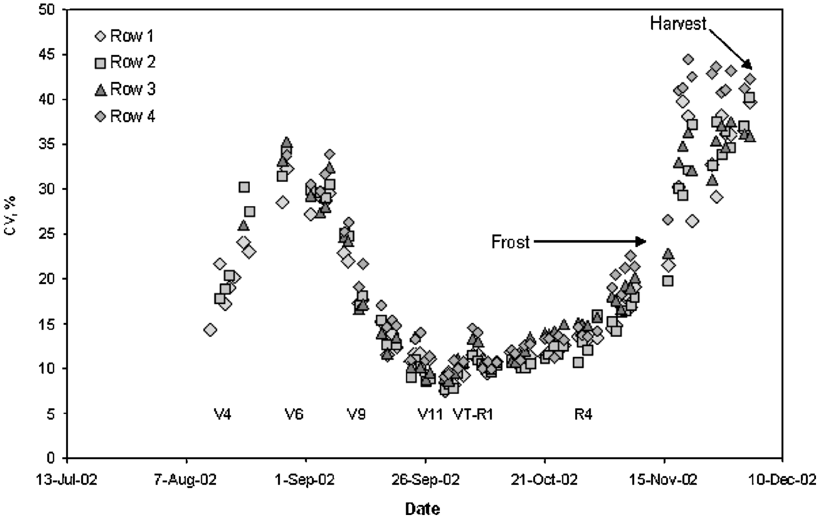

Figure 2. Relationship between the coefficient of variation (CV) for normalized difference vegetative index (NDVI) sensor readings collected from 4 corn rows, August to October, 2002, Texcoco, Mexico.

close. It was interesting to note that when several plants were closely spaced together, sensor readings were higher, with corresponding lower plant yields (Fig. 3). Higher plant density would be expected to lead to decreased by-plant yields. Inherent errors matching sensor readings to plant yields were a function

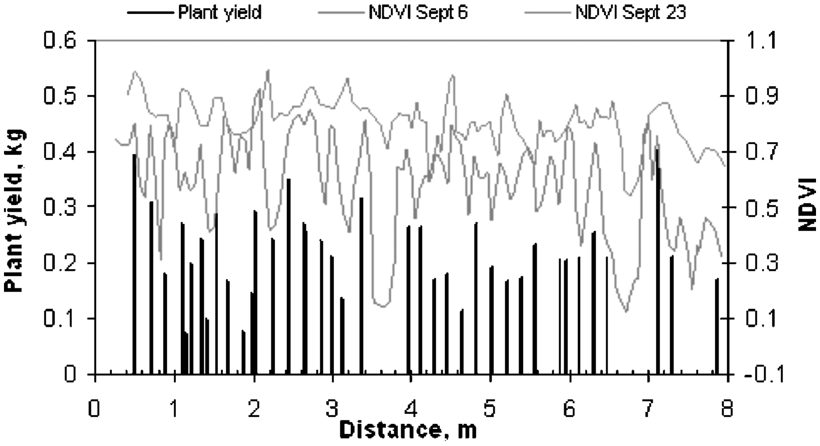

Figure 3. By-plant yield (entire plants, stalk + ear harvested at the base) over 6 m of row, and corresponding normalized difference vegetative index (NDVI) sensor readings collected from this same area at the 7 leaf and 10 leaf growth stages, 87 and 70 days earlier, Texcoco, Mexico, 2002.

of sensor readings triggered on a time rather than distance basis. Because of this, NDVI readings could not be precisely matched to specific plants.

DISCUSSION

Once the canopy began to close at V6, leaves from larger plants covered the leaves and whorl of smaller plants, extending further into the linear row. As these leaves began to fill the row, intersecting with and in some cases covering up leaves from smaller plants, two things happened. First, soil coverage decreased, and the amount of green vegetation visible increased, increasing NDVI. Second, the ability to detect by-plant differences (plants spaced 20 cm apart with a sampling frequency of 5 cm) decreased, and the detectable by-plant variability diminished. This is especially apparent in Fig. 3, where low NDVI values were periodically detected from in-row sensor readings before the canopy had completely closed at V8 (September 9, 45 days after planting). Low NDVI values are the result of sensing bare soil associated with uneven plant stands and some missing plants, and these same low spots were no longer obvious by V10 (September 23, 59 days after planting), and thus the reason for the much lower CV.

The first peak in CVs at V6 could represent the best time to apply in-season foliar N fertilizer, as this was the time when spatial variability of NDVI values was greatest (Fig. 2). This assumes that the spatial variability encountered at this stage of growth could also be correlated with final estimates of yield potential, and that a response to applied N (based on estimated yield potential) could be achieved. Work by Raun et al. (2001) demonstrated that accurate mid-season estimates of yield potential were indeed possible using NDVI readings collected at vegetative stages of growth in winter wheat. Later work by Raun et al. (2002) showed that N fertilization based on mid-season estimates of yield potential increased nitrogen use efficiency (NUE) by more than 15% when compared to traditional practices at uniform N rates. However, this same concept has not yet been applied and tested in corn.

The second CV peak occurred just between VT and R1 (which begins when any silks are visible outside the husks; VT generally begins 2–3 days before silks emerge ISU, 2). The window for detecting the transition between VT and R1 is obviously quite small (2–3 days). However, it is precisely this transition that resulted in the increased CVs between October 4 to 6, 2002. Over this period, some of the tassels were completely visible, while others were just emerging. The light yellow-green color present in the tassels (plants 1–2 days ahead of the rest) resulted in decreased NDVI readings, while plants with more immature tassels had darker green colors and higher average NDVI. It was precisely this spatial difference in colors (present only for 2 days) that led to the increased CVs. Once all the tassels had emerged (1–2 days later), the CVs again dropped, due to the uniformity in color detected by the sensor.

What would appear to a casual observer to be a rather homogeneous cornfield was visibly more heterogeneous over this 2-day period. Neighboring plants were in many places found to differ on days to emergence between 7 and 12 days. These differences in emergence were also later reflected in the disparity in tassel emergence. In spite of a distinguishable second peak in CVs, this spike would not be one that could be used to apply N fertilizers simply because the CVs were much lower than earlier in the season and because the window of opportunity was extremely narrow.

Immediately following the point where tassel emergence increased, CVs due to morphological disparity (some plants with tassels emerged, and some without), CVs decreased to near 10%. Once all plants had tassels fully visible, CVs remained below 12.7% for 15 days. Beyond that time (87 days after planting), CVs again rose steadily, increasing substantially 97 days after planting (Fig. 2). The increase in CVs 97 days after planting corresponded to the R4 stage corn in growth, where rapid leaf senescence was visible in the field. At this stage of growth, a noticeable decrease in mean NDVI values was observed (Fig. 1), consistent with the expected change in leaf color.

The ability of the by-day NDVI readings to detect the stage of growth where the maximum amount of within-row-by-plant variability was expressed is an exciting prospect. Is the stage of growth with the maximum within-row-by-plant variability the same stage at which treating that variability will have the greatest impact? This has not been determined in either wheat or corn; however, our work would suggest that the point (V6) where by-plant variability was best recognized should theoretically be the same time at which to sense and treat spatial variability. Also, assuming that by-plant variability or changes in biomass could be accurately recognized, by-plant fertilization based on yield potential appears quite plausible. It is important to note that the peak in early-season CVs was followed by another peak in CVs as corn plants approached maturity. From the V9 to R4 growth stages, the variability in plant spacing/growth was masked due to overlapping leaves and canopy closure. After R4, and with more rapid senescence, sloughing off led again to recognizing the same spatial variability encountered early in the season. At a sampling frequency of 5 cm, with plants spaced 21 ± 7 cm apart, pre-canopy fill and subsequent closure could most definitively be detected in NDVI readings (high CVs followed by a plateau of lower CVs). This is also an exciting prospect, as past work has shown that early season NDVI readings in other crops have been highly correlated with total biomass and yield potential.

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