By-Plant Prediction of Corn Forage Biomass and Nitrogen Uptake at Various Growth Stages Using Remote Sensing and Plant Height

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ABSTRACT

As research intensifies on developing precision agricultural practices for corn (*Zea mays* L.) production, an important component will be to identify the scale at which these practices should be implemented. We hypothesized that optical sensing can be used to measure individual corn plant biomass and N uptake. A 3-yr study was conducted at three locations in Oklahoma. Optical sensor readings of normalized difference vegetation index (NDVI) and plant height measurements were collected on individual corn plants at various growth stages ranging from V8 (collar of eighth leaf unfolded) to VT (last branch of the tassel is completely visible) and correlated with individual plant biomass, forage yield per unit area occupied by the plant, and N uptake of that plant. Individual plant height measurement, collected before reproductive growth, was a good predictor of plant biomass across the six site years of the study ($r^2 = 0.81$). The index of NDVI × plant height provided the highest correlation with by-plant forage yield on an area basis. Optical sensor and plant height measurements collected at the V8 to V10 (collar of 10th leaf unfolded) growth stage can distinguish individual plants and provide information as to their biomass accumulation and N uptake. This research demonstrates that by-plant information can be collected and used to direct high resolution N applications. The index, NDVI × plant height, may be used to refine midseason fertilizer N rates based on expected N removal and by-plant measurements at or before V10.

As PRECISION FARMING becomes accepted and adopted, delineating the proper field element size for management inputs becomes more important. Sadler et al. (2000) studied the effects of soil variation on crop phenology, biomass, and yield components of corn under drought. Their experiment analyzed detailed soil maps at a scale of 1:1200 and extensive sampling of crop characteristics across an 8-ha field. The results indicated that grain yield variation within a soil map unit was too large for the soil survey alone to be used to create homogenous soil management zones for use in precision farming. Sadler et al. (2000) went on to state that these results supported the need for on-the-go measurements of soil properties and plant response that could be used in conjunction with soil surveys to create management zones that can be used in models, or by themselves, to predict grain yield.

Solie et al. (1996) defined field element size as the area that provides the most precise measure of the available nutrient and where the level of that nutrient changes with distance. This work went on to suggest that the fundamental field element size averages 1.5 m^2. A microvariability study by Raun et al. (1998) found significant differences in surface soil test analyses when samples were <1 m apart for both mobile and immobile nutrients. Solie et al. (1999) stated that to describe the variability encountered in field experiments, soil, plant, and indirect measurements should be made at the meter or submeter level. Similarly, Raun et al. (2002) reported that for optimal N management of wheat (*Triticum aestivum* L.), 1-m^2 areas in fields need to be sensed and managed independent of adjacent 1-m^2 areas.

Identifying and understanding the variability among plant-to-plant spacing within the row is also crucial for precision farming techniques. This variability is usually due to the combination of crowded plants (doubles, triples, etc.) and long gaps or skips (Norwood and Currie, 1996). It is possible that plants next to gaps can compensate for loss of area and produce larger ears, but they generally cannot compensate enough for the smaller ears of the crowded plants that also are competing strongly for sunlight, water, and nutrients. A growth stage difference of two leaves or greater between adjacent plants in a row will almost always result in the later developing plant being barren at harvest (Nielson, 2001). Nielson further determined plant spacing variability (PSV), which is the standard deviation of the plant spacing within a representative row in a field. Among 350 production corn fields in Indiana and Ohio, 16% had a PSV of three inches or less, 60% had a PSV of three to five inches, and 24% of the fields had a PSV of six inches or greater. Further research showed that for every 2.5 cm in PSV above a value of 5 cm, about 157 kg ha^{-1} of yield loss occurred.

In 1996, Stone and colleagues investigated the use of hand-held sensors to detect and predict forage N uptake and grain yields in winter wheat (Stone et al., 1996a, 1996b). These sensors measured red and near infrared (NIR) irradiance from the crop, which was used to calculate NDVI. They found NDVI was highly correlated with forage N uptake and grain yields of winter wheat. Katsvairo et al. (2003) studied how biomass, N concentrations, and N uptake could be used to facilitate variable rate N management. They found that these factors

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Abbreviations: FWHM, full width half magnitude; GDD, growing degree days; LCB, Lake Carl Blackwell; NDVI, normalized difference vegetation index; NIR, near infrared; PSV, plant spacing variability.

had no spatial variability at the V6, R1, and R6 growth stages. However, they did state that plant height showed significant spatial variability but did not consistently correlate with corn yields in a dry year, but they recognized that more research should be conducted on plant height measurements. A study by Machado et al. (2002) revealed that by using plant height, 90 and 61% of the variation in total dry matter and grain yield, respectively, could be explained in a dry year. These data are supported by Sadler et al. (1995), who reported that differences in phenology, biomass, leaf area, and yield components were most pronounced under drought.

Teal et al. (2006) evaluated growing degree days (GDD), NDVI normalized for GDD, and NDVI to predict yield potential of corn. Their results showed that normalizing NDVI for GDD explained about 73% of variability in predicted grain yield. Martin et al. (2006) reported that NDVI increased until a plateau was attained at V10 and decreased after the VT growth stage. They generalized that the highest correlation of NDVI with corn grain yield was found at the V7 to V9 growth stages. A study initiated to evaluate by-plant corn grain yield variability across a range of production environments revealed that averaging yield across distances > 0.5 m removed the extreme by-plant variability and suggested 0.5 m as a scale for treating other factors affecting yield (Martin et al., 2005). Previous research however, did not address the relationship between NDVI and height and in-season measurements such as biomass, forage yield, and forage N uptake. The objective of this study was to relate measurements of by-plant reflectance and plant height with corn forage biomass, corn forage yield, and corn forage N uptake.

MATERIALS AND METHODS

Two field experiments were initiated in spring 2003 to evaluate the use of sensor readings for predicting by-plant total biomass and N uptake. The locations included Efaw and Perkins research stations in 2003 and 2004. In 2005, experiments were located at the Efaw research station and at the Lake Carl Blackwell (LCB) irrigated research farm. The soil at Efaw is classified as Easpur loam (fine-loamy, mixed superactive thermic Fluventic Haplustoll). Perkins is classified as Teller sandy loam (fine, mixed, thermic Udic Argiustolls). Soil classification of the LCB experiment is Pulaski fine sandy loam (coarse/loamy, mixed nonacid, thermic, Typic, Ustifluvent). Corn hybrid 33B51 (Pioneer Hi-Bred International Inc., Johnston, IA) was planted at each location with a John Deere (Moline, IL) MaxEmerge planter at a target plant population of 51 000 plants ha^{-1} at Efaw and Perkins, and 71 000 plants ha^{-1} at LCB. All locations were planted with a row spacing of 0.76 m. All crop management practices were performed as per the Oklahoma State University, Plant and Soil Sciences Department recommendations for respective locations.

For each location and forage harvest, 13 to 17 m of row was identified that included exactly 50 corn plants. Three forage harvests of 50 individual plants were taken at each location at various growth stages (Table 1). Each plant was sensed using a GreenSeeker Hand Held (NTech Industries, Ukiah, CA) active (generates its own illumination source to measure NDVI) optical sensor that was mounted to a bicycle with a shaft encoder to log distance (one reading per cm of linear distance traveled) with each NDVI reading collected.

The GreenSeeker Hand Held Optical Sensor Unit was used to collect NDVI measurements. The unit senses a 0.6- by 0.01-m spot when held at a distance of ≈0.6 to 1.0 m from the surface. The sensor unit has active, self-contained illumination in both the red [650 ± 10 nm full width half magnitude (FWHM)] and NIR (770 ± 15 nm FWHM) bands. The sensed dimensions remain approximately constant over the height range of the sensor. The device measures the fraction of the emitted light in the sensed area returned to the sensor (reflectance or ρ) and computes the NDVI according to the following formula:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{red}}}$$

where ρ_{NIR} = the fraction of emitted NIR radiation returned from the sensed area (reflectance), and ρ_{red} = the fraction of emitted red radiation returned from the sensed area (reflectance).

The sampling rate was ≈1000 measurements s^{-1}, and these measurements were averaged for each output (each cm). The sensor was passed over the crop at a height of ≈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. It is important to note that some overlapping leaves were expected at later stages of growth, but this morphological variability was not accounted for in this work. The mean NDVI was computed for each plant. Growth stages in corn were identified using the terminology developed at Iowa State University (1993).

Immediately after sensing, each plant was cut at ground level and wet weights were recorded by plant. Each plant was then dried at 75°C for 4 d and dry weights subsequently recorded. Dry plant material was then ground to pass a 240-mesh

Table 1. Planting and harvest dates, growth stages, days from planting to forage harvest (DFP), and populations (Popu) of rows used for harvesting at each of the three corn biomass harvesting dates in the by-plant corn experiment at Efaw, Perkins, and Lake Carl Blackwell, OK, 2003 to 2005.

		First harvest				Second harvest				Third harvest			
	Planted	Date	Stage†	DFP	Popu	Date	Stage	DFP	Popu	Date	Stage	DFP	Popu
					Plants ha^{-1}				plants ha^{-1}				plants ha^{-1}
2003													
Efaw	31 March	22 May	V8	52	49 524	2 June	V10	63	49 602	18 June	VT	79	53 017
Perkins	2 April	23 May	V8	51	41 968	2 June	V10	61	43 122	18 June	VT	77	45 670
2004													
Efaw	7 April	2 June	V8	56	68 377	14 June	V11	68	66 151	8 July	R1	92	70 462
Perkins	2 April	2 June	V8	61	48 028	14 June	V11	73	49 379	8 July	R1	97	43 506
2005													
Efaw	7 April	8 June	V9	61	51 127								
Lake Carl Blackwell	26 April	17 June	V9	52	63 400								

† Corn growth stages as defined by Iowa State University (1993) as follows: V8, V9, V10, and V11 are defined as collar of 8th, 9th, 10th, and 11th leaf unfolded, respectively; VT is defined as the last branch of the tassel is completely visible; R1 is defined as sliking.

Table 2. Average temperature and total rainfall during corn growing months at Efaw, Lake Carl Blackwell, and Perkins, OK, 2003–2005.

	Avg. air temperature				Rainfall			
Month	**2003**	**2004**	**2005**	**35-yr avg.**	**2003**	**2004**	**2005**	**35-yr avg.**
	°C				mm			
Efaw								
April	15.9	15.6	15.8	15.0	34.8	70.3	9.8	81.3
May	20.0	22.0	20.4	23.6	83.5	5.8	96.3	123.9
June	23.1	23.5	25.7	24.6	104.8	227.0	95.8	105.4
July	29.2	25.8	26.8	27.6	15.8	109.3	80.3	66.1
August	28.4	24.5	26.7	26.9	76.8	42.5	219.3	76.4
September	20.1	23.1	24.3	22.5	74.3	19.0	74.3	97.2
Lake Carl Blackwell								
April	16.2	15.6	15.7	15.4	38.3	73.8	10.5	116.5
May	19.8	21.5	20.2	20.3	86.0	3.5	68.0	105.1
June	22.9	23.3	25.0	24.3	135.8	191.5	150.3	144.1
July	28.9	25.4	26.2	27.3	11.5	55.5	109.0	102.4
August	28.4	24.4	26.7	27.2	74.3	60.3	242.5	105.0
September	20.4	23.5	21.2	22.5	68.3	43.5	89.2	93.0
Perkins								
April	16.1	15.6	15.0	15.8	45.0	33.3	125.2	85.0
May	20.5	22.2	19.2	21.4	159.8	31.5	181.6	94.1
June	23.5	23.8	23.5	23.7	141.0	176.3	250.4	126.6
July	29.7	25.9	28.0	27.8	12.2	94.5	82.3	76.5
August	28.8	24.8	28.2	26.8	100.6	51.6	97.0	68.0
September	20.4	23.9	21.5	22.2	89.7	17.5	115.3	87.9

screen and analyzed for total N using a Carlo-Erba dry combustion unit (Schepers et al., 1989).

To determine corn forage yield on an area basis, the area that each individual plant occupied was measured by taking the distance halfway to the plant in front and behind it. This determined the linear dimension and was then multiplied by the row width of 0.76 m to calculate the area for a given plant. The NDVI readings for each plant were determined in the same fashion, whereby sensor readings half the distance to the neighboring plant in front of and behind the plant being measured were averaged. This was accomplished by employing the shaft encoder since distance and NDVI were written to the data file. Because total distances and distances between plants were recorded previously, sensor data could be partitioned accordingly.

Plant heights were also recorded for each individual plant before harvest. Plant height was determined by extending the last collared leaf upright. For the third cutting, the corn height was measured to the top of the tassel.

An index was calculated by multiplying NDVI readings and plant height to assess a pseudo three-dimensional image of total biomass. In an attempt to more accurately predict corn forage biomass, the data were divided into two groups based on growth stage. The first group consisted of corn plants harvested between the V8 (collar of eighth leaf unfolded) and V10 (collar of 10th leaf unfolded) growth stages (<65 d from planting to harvest). The second group consisted of corn plants harvested between growth stages V11 (collar of 11th leaf unfolded) and R1 (silking) stages (>65 d from planting). Sidedress N applications are not often made after V10, thus why the two distinct groups were used for analyses. Also, past research showed that NDVI values measured between corn growth stages V8 and V10 were similar (Martin et al., 2006). Table 1 describes growth stage and days from planting to harvest. Air temperature and rainfall at each of the experimental sites during the study are summarized in Table 2. Plant populations were variable across harvest, locations, and years (Table 1). The Efaw location had consistently higher populations than the Perkins locations in 2003 and 2004. In 2005, the LCB site was under sprinkler irrigation. Linear and nonlinear regression analysis was done using plant height, NDVI, and NDVI × height index (the product of NDVI and plant height) as independent variables and corn forage biomass (g per plant not accounting for area occupied by the plant), corn forage

Table 3. Relationship between independent and dependent variables at two ranges of corn growth stages for the by-plant corn experiment data averaged across locations and years in Oklahoma.

	Variable			
Growth stage of corn†	**Independent**	**Dependent**	**Model type**	**r^2‡**
V8–V10	NDVI§	Biomass, kg plant^{-1}	exponential	0.31*
V11–R1	NDVI	Biomass, kg plant^{-1}	exponential	0.20ns¶
V8–V10	Area, m^2 plant^{-1}	Biomass, kg plant^{-1}	–#	–
V11–R1	Area, m^2 plant^{-1}	Biomass, kg plant^{-1}	–	–
V8–V10	Area, m^2 plant^{-1}	Height, cm	linear	0.03ns
V11–R1	Area, m^2 plant^{-1}	Height, cm	linear	0.08ns
V11–R1	NDVI	Forage yield, Mg ha^{-1}	linear	0.37*
V11–R1	Height, cm	Forage yield, Mg ha^{-1}	linear	0.43*
V8–V10	Height, cm	N uptake, kg ha^{-1}	linear	0.26ns
V11–R1	Height, cm	N uptake, kg ha^{-1}	linear	0.45**
V8–V10	NDVI × Height	N uptake, kg ha^{-1}	exponential	0.46**

* Model significant at the 0.05 level of probability.

** Model significant at the 0.01 level of probability.

† Corn growth stages as defined in Table 1 by Iowa State University (1993).

‡ r^2 denotes the proportion of variability in the dependent variable explained by the independent variable by the selected model.

§ Normalized difference vegetative index.

¶ ns, not significant.

No relationship between dependent and independent variables was observed.

yield per area (g of biomass accounting for area occupied by plant), and corn forage N uptake (forage yield × N concentration of measured forage) as dependent variables. Selection of the best fit model to the data was identified using the residual standard deviations and highest coefficient of determination (r^2) criterion.

RESULTS AND DISCUSSION

Biomass

Across years and locations, there was a weak but significant relationship between NDVI and plant biomass for data collected from corn growth stages V8 to V10 (Table 3). As noted above, NDVI was calculated and measured for each corn plant by averaging sensor readings from half the distance to the preceding plant and half the distance to the following plant in a row. With unequal spacing often incurred by mechanized corn planting, the area occupied by individual corn plants varied. This variation in plant spacing affected the ability of NDVI alone to predict dry corn biomass at early and late stages of growth. Teal et al. (2006) showed that at the V8 corn growth stage corn biomass has strong ($r^2 = 0.77$) relationship with NDVI. Optical sensor and plant height measurements collected at the V8 to V10 growth stage can distinguish individual plants and provide information as to their biomass accumulation and N uptake.

Height and biomass were highly correlated independent of the area the plant occupied, and the correlation with forage biomass was much better at earlier stages (Fig. 1) than later stages (Fig. 2). This is important because it indicates that height alone can be used to estimate plant biomass without having to compensate for the area occupied by the plant. Using data from the V8 to V10 growth stages, the area occupied per plant was not related to either dry biomass per plant or plant height (Table 2). These combined results (no correlation of area with either height or biomass) indicate that area was not an important variable in the prediction of dry biomass using the populations and hybrids employed in this trial. When areas were partitioned into the following categories (area < 0.2 m^2 or > 0.2 m^2), the resultant correlations were nearly identical, again suggesting the independence of these relationships as a function of area (data not shown).

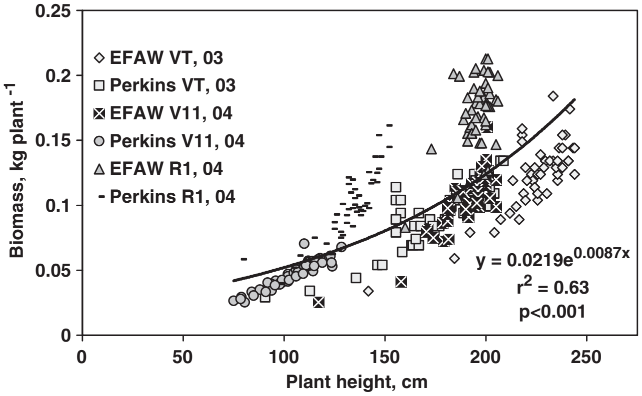

Fig. 2. Relationship between plant height and dry plant biomass for individual corn plants at growth stages ranging between V11–R1 at Efaw and Perkins, in 2003 and 2004.

The index of NDVI × height was a good predictor of plant biomass (Fig. 3 and 4) though plant height alone was a more accurate predictor. A linear regression performed between the NDVI × height index and plant biomass at early growth stages resulted in an r^2 value of 0.66. At the later growth stage, r^2 value obtained using the NDVI × height index was 0.45.

Forage Yield

Across years and locations, NDVI accurately predicted forage yields accounting for area at earlier stages of growth (Fig. 5 and Table 2). This improved relationship between NDVI and corn forage yield at earlier growth stages is explained by increased sensitivity of NDVI. When corn is younger and smaller, the sensor has the ability to detect more soil area of lower-yielding plants compared with higher-yielding plants. Conversely, at later stages of growth corn plants were taller, which required increased elevation of the sensor and subsequently the soil background had a diminished influence on NDVI. The lower plant populations and poor growing conditions at Perkins consistently produced

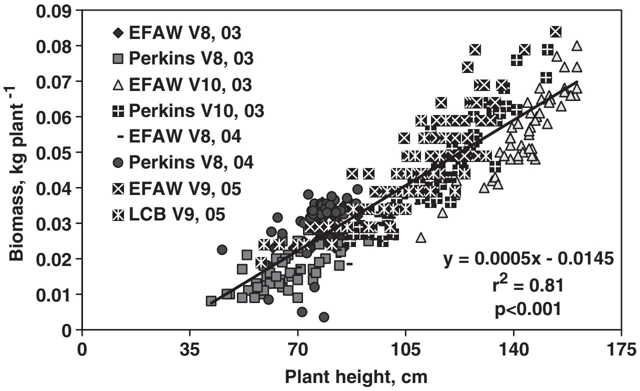

Fig. 1. Relationship between plant height and dry plant biomass for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell, in 2003, 2004, and 2005.

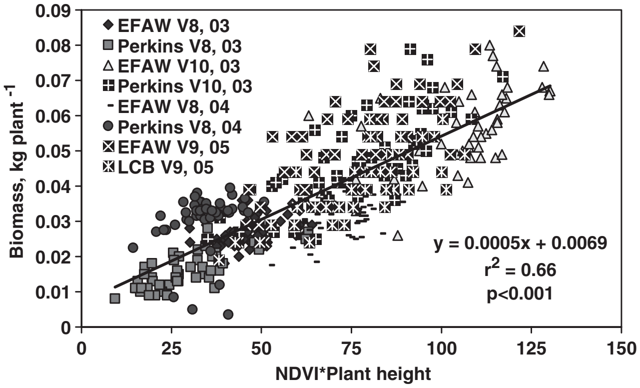

Fig. 3. Relationship between the product of NDVI and plant height and dry plant biomass for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell in 2003, 2004, and 2005.

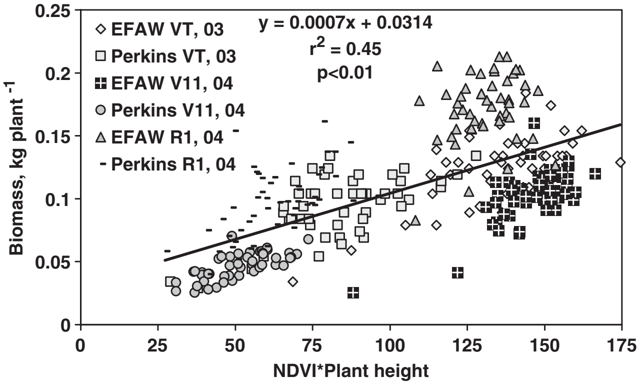

Fig. 4. Relationship between the product of NDVI and plant height and dry plant biomass for individual corn plants at growth stages ranging between V11–R1 at Efaw and Perkins, in 2003 and 2004.

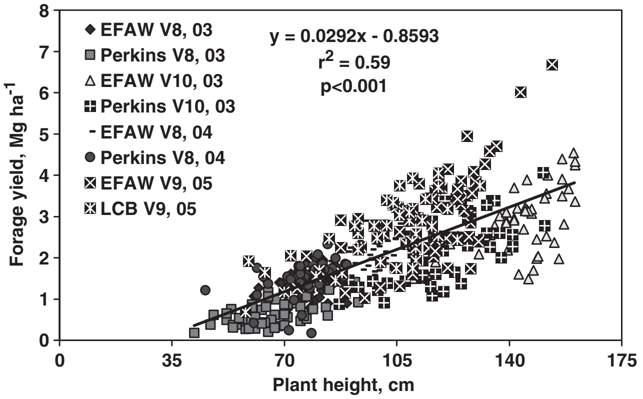

Fig. 6. Relationship between plant height and dry biomass yield for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell in 2003, 2004, and 2005.

lower-yielding plants and lower NDVI values than the Efaw location.

Plant height measurements were also used to predict corn forage yield accounting for area. At growth stages ranging from V8 to V10, plant height predicted forage yield similar to NDVI. However, at later growth stages, plant height was a better predictor of forage yield than NDVI based on the model r^2 value (Fig. 6 and Table 2). For the duration of this experiment, location, growth stage, and year tended to produce distinct data clusters when plant height and forage yield were plotted. This observation was not noted when plant height was correlated with by-plant dry biomass at the early growth stages (Fig. 1). This further explains the ability of plant height to predict biomass, and the finding that there is little benefit in considering the area that the plant occupies across locations and growth stages of this experiment (Fig. 1).

The NDVI × plant height index was also correlated with corn forage yield accounting for area. This index proved to be a better predictor of corn forage yield than either NDVI or plant height alone (Fig. 7 and 8) at both early ($r^2 = 0.62$) and later ($r^2 = 0.64$) stages of growth. The index of NDVI × plant height is expected to lead to improved prediction of grain yield potential, and that can subsequently be used to refine midseason fertilizer N rates based on expected N removal. This follows work by Raun et al. (2002) that documented increased N use efficiency when using projected differences in N uptake between N rich and farmer practice as the criterion for prescribing midseason N.

Nitrogen Uptake

The amount of N taken up in corn forage was highly correlated with NDVI (Fig. 9 and 10). At early stages of growth, NDVI explained 64% of the variation in N uptake. This correlation was slightly lower ($r^2 = 0.61$) at later growth stages. In both cases, NDVI proved to be a better predictor of N uptake than forage yield or plant biomass (data not shown). The strong correlation between NDVI and N uptake could be explained by the ability of NDVI to detect differences in red absorption and variation in chlorophyll content. Thomas and Oerther (1972) noted similar finding in sweet peppers (*Capsicum annum* L.); the reflectance of the visible portion of the spectrum (500–700 nm) increased as N-deficiency symptoms became more pronounced. However, no significant ($p < 0.05$) relationship was noted between NDVI and tissue N concentration in corn

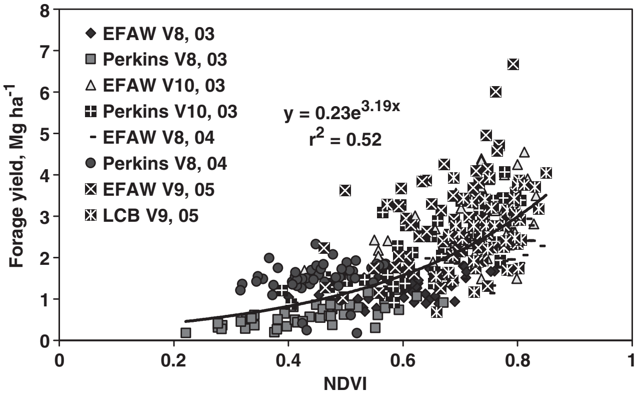

Fig. 5. Relationship between NDVI and dry biomass yield for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell in 2003, 2004, and 2005.

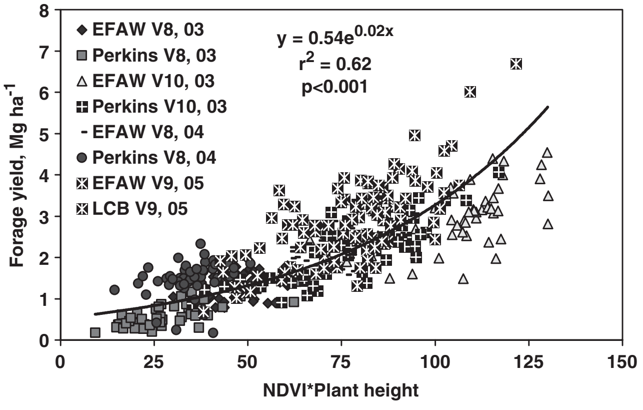

Fig. 7. Relationship between the product of NDVI and plant height and dry biomass yield for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell in 2003, 2004, and 2005.

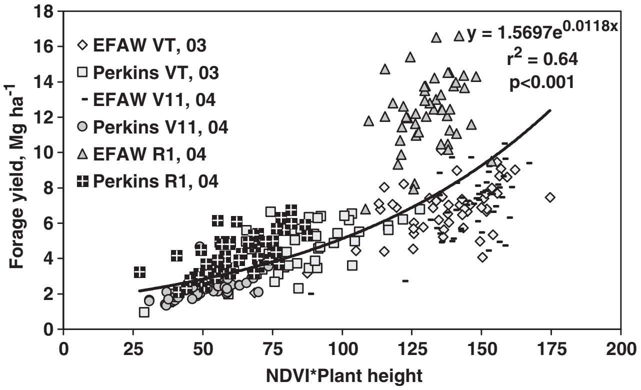

Fig. 8. Relationship between the product of NDVI and plant height and dry biomass yield for individual corn plants at growth stages ranging between V11–R1 at Efaw and Perkins in 2003 and 2004.

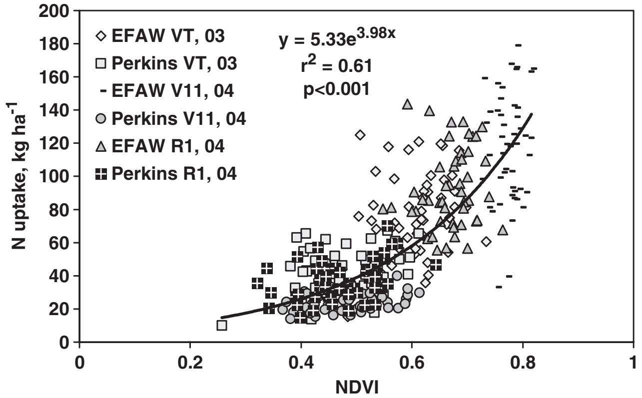

Fig. 10. Relationship between NDVI and corn forage N uptake for individual corn plants at growth stages ranging between V11–R1 at Efaw and Perkins in 2003 and 2004.

forage across years, locations, and growth stages (data not reported).

At early and late stages of growth, plant height was not as accurate a predictor of N uptake in the forage as NDVI (Table 2). But, at later growth stages, there was a significant correlation between plant height and N uptake than earlier growth stages. A relationship was present between plant height and N uptake at early growth stages; however, this relationship differed based on growth stage and location. Forage harvested between V8 and V9 at Efaw in 2004 and LCB in 2005 took place following early irrigations. This may have allowed for favorable growing conditions that led to increased N uptake compared with the other locations that were harvested at early growth stages, but where moisture was limiting. This difference in growing conditions resulted in significant variability and has decreased correlation between plant height and N uptake at growth stages V8 to V10. At later growth stages, the relationship of plant height and NDVI was much improved, as compared with earlier growth stages.

The NDVI × plant height index was also a good predictor of N uptake in corn forage. Similar to plant height, this index had a much stronger relationship with N uptake at later growth stages compared with earlier stages of growth. The V8 to V10 growth stages did show a correlation with N uptake, but this relationship was not consistent across locations (Table 2). The NDVI × height index expressed a strong relationship with N uptake ($r^2 = 0.77$) using an exponential model for corn forage harvested from V11 to R1 growth stages (Fig. 11). A weaker correlation ($r^2 = 0.46$) was obtained at V8 to V10 growth stages.

CONCLUSIONS

The objective of this experiment was to determine if corn forage biomass, corn forage yield, and corn forage N uptake could be accurately predicted using by-plant sensor data and plant height collected at various stages of corn development. Results showed that forage biomass, forage yield, and forage N uptake could be accurately predicted using indirect measures. By-plant forage yields, accounting for area occupied by the plant, were accurately predicted using the index NDVI × plant height. Forage yields were also correlated with NDVI and plant height individually. These relationships with forage yields were consistently better at early stages of growth. The best predictor of forage N uptake was NDVI alone when compared with plant height and the index of NDVI × height at early growth stages. There was a better relationship with plant height

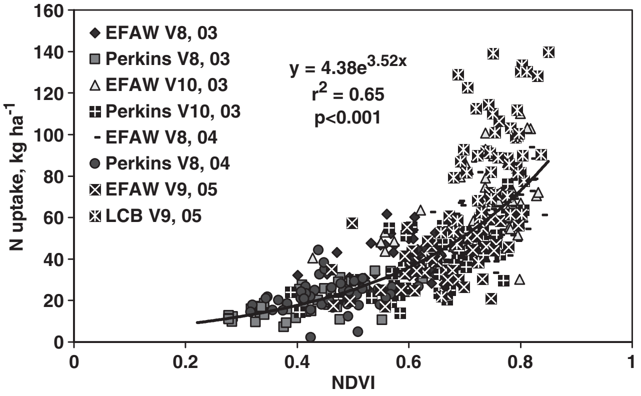

Fig. 9. Relationship between NDVI and forage N uptake for individual corn plants at growth stages ranging between V8–V10 at Efaw, Perkins, and Lake Carl Blackwell in 2003, 2004, and 2005.

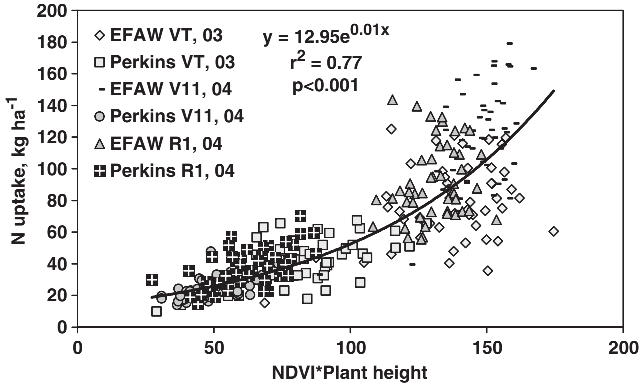

Fig. 11. Relationship between the product of NDVI and plant height and corn forage N uptake for individual corn plants at growth stages ranging between V11–R1 at Efaw and Perkins in 2003 and 2004.

and plant biomass, without accounting for the area occupied by the plant than when forage yield was calculated using area occupied. This suggests that plant height was independent of the area occupied by the plant. Changes in height and biomass were independent of the area occupied by corn for the in-row variability encountered in these experiments. The index of NDVI × plant height is expected to lead to improved prediction of grain yield potential and that can subsequently be used to refine midseason fertilizer N rates based on expected N removal. Optical sensor and plant height measurements collected at the V8 to V10 growth stage can distinguish individual plants and provide information as to their biomass accumulation and N uptake. This shows that by-plant information can be collected and that this information can be used to direct high resolution N applications.

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