Spatial and Temporal Variability of Corn Growth and Grain Yield: Implications for Site-Specific Farming

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ABSTRACT

Effects of factors influencing spatial and temporal variability of crop yields are usually expressed in crop growth patterns. Consequently, monitoring crop growth can form the basis for managing site-specific farming (SSF). This experiment was conducted to determine whether crop growth patterns forecast grain yields. Effects of irrigation rates (50 and 80% evapotranspiration, ET), elevation, soil texture, soil NO_3-N, arthropods, and diseases on corn (*Zea mays* L.) growth and grain yield were evaluated at Halfway, TX, in 1998 and 1999. Data on plant height, leaf area index, leaf dry matter, stem dry matter, and ear dry matter were collected from geo-referenced locations (DGPS). These data were used to derive total dry matter, crop growth rate, and net assimilation rate (NAR). Grain yields at DGPS locations were classified into four distinct clusters. In 1998, a dry season, clusters were strongly influenced by elevation and soil texture. Grain yields were higher at high elevations where water use was high and soil texture was heavy compared with low elevations. Grain yields at low elevations also were reduced by common smut [*Ustilago zeae* (Beckm.) Unger] that preferred dry conditions. In 1999, a relatively wet season, clusters included areas with different elevation and soil texture combinations. Measured parameters forecast grain yields better in 1998 than in 1999. Differences in NAR were evident before the 12-leaf stage, making NAR a potentially useful measurement for early in-season management decisions. Biomass measurements, for which differences were observed after the 12-leaf stage, also may be used to formulate decisions for both in-season and the following season's management.

Managing SSF is currently based on information about soil physical and chemical characteristics (Robert et al., 1996, 1998). While this information is useful in the demarcation of management zones for fertilizer application, observed crop yields have not always followed trends in soil physical and chemical characteristics. Interactions among biotic and abiotic factors influence spatial variability of crop yields (Soluhub et al., 1996; Pan et al., 1997; Mulla and Schepers, 1997; Sadler and Russell, 1997; Braum et al., 1998; Machado et al., 2000; Sadler et al., 2000). Biotic factors include plant genotype, soil fauna, pests, and diseases, and abiotic factors include soil physical, chemical, and moisture characteristics, and climatic conditions. Effects of soil physical and chemical factors on crop yields are predictable (Moran et al., 1997; Machado et al., 2000) and can be mapped relatively easily. These attributes make soil physical and chemical characteristics obvious targets for variable rate technology (VRT).

Effects of crop stress (due to drought and nutrient deficiency), pests, and diseases on crop yield, however, are temporal and difficult to predict (Moran et al., 1997; Pan et al., 1997; Machado et al., 2000). Temporal effects explain more than 50% of crop yield variability across years and sites (Huggins and Alderfer, 1995; Clarke et al., 1996). Hence, improvements in the control and management of some temporal effects may lead to substantial gains in grain yield and profitability. Managing factors that influence the temporal variability of crop yields is a major challenge to farmers, and ways should be developed to simplify management of these factors. Since plants integrate all factors influencing their growth and productivity, monitoring plant growth may provide useful information on how biotic and abiotic factors are interacting and influencing crop yields. Management of SSF can greatly benefit from information on spatial and temporal variability in crop growth patterns.

Crop monitoring not only improves control of temporal variation in crop growth, but also provides information on crop development that is useful in developing management strategies that improve water and nutrient use efficiency. Water and nutrient applications made at periods of peak demand improve water (Passioura, 1994) and nutrient (Baethgen and Alley, 1989) use efficiency and increase grain yields. Furthermore, the efficient use of nutrients reduces groundwater pollution (Hall, 1992; Phillips et al., 1993) and can result in N savings without reductions in grain yields (Stone et al., 1996). Despite these benefits, SSF research on crop monitoring lags behind VRT research. Most SSF research has concentrated on soil physical characteristics and VRT for N. Less than 2% of all research on SSF (Robert et al., 1996, 1998) was on the understanding of plant response to SSF or on effects of multiple stresses and inputs on plant growth and development. The success of SSF, however, depends on our ability to control temporal variations in crop growth caused by the interactions among biotic and abiotic factors. The VRT fertilizer application approaches can benefit from information on the spatial and temporal variability of crop growth.

Most research work on plant monitoring has been done by remote sensing (Nilsson, 1995; Moran, 1997). The main emphasis has been to increase the accuracy of estimating crop biomass (Bedford et al., 1993), leaf area index (LAI) (Bouman et al., 1992), nutrient defi-

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Abbreviations: CGR, crop growth rate; DGPS, differential global positioning system; EDM, ear dry matter; ET, evapotranspiration; LAI, leaf area index; LDM, leaf dry matter; LEPA, low energy precision application system; NAR, net assimilation rate; SDM, stem dry matter; SI, soil index; SSF, site-specific farming; TDM, total plant dry matter; VRT, variable rate technology.

ciency (Thomas and Oerther, 1972; Peñuelas et al., 1994), water stress (Peñuelas et al., 1993, 1994; Ripple, 1986), arthropod infestation (Riedell and Blackmer, 1999), and diseases (Nilsson, 1995; Pederson and Nutter, 1982). However, little effort has gone into relating these measurements to the final grain yield (Blackmer et al., 1994, 1996; Zhang et al., 1998) and determining how this information could be used for managing SSF. In these studies, high correlations between crop yields and remote sensing measurements were obtained late in the growing season (Blackmer et al., 1994, 1996; Zhang et al., 1998). This information is useful in demarcating management zones for the next season provided poor plant growth was caused by factors like soil physical characteristics. If the causes of poor plant development are random, such as pests and diseases, then early detection of trouble spots in the field is required to allow for remedial action to be taken.

We hypothesize that spatial variability in grain yields can be quantified early in growing season through growth analysis. The objectives of this experiment were to (i) determine whether grain yields of corn could be predicted early in the season from growth analysis measurements, and (ii) to use this information in the formulation of decisions for managing SSF. To address these objectives, the effects of water, elevation, soil texture, pests, and diseases on crop growth and grain yield were evaluated on irrigated corn.

MATERIALS AND METHODS

Experimental Layout

This experiment was conducted in 1998 and 1999 at the Texas A&M University System Agricultural Research and Extension Center at Halfway, TX (101° 57′ W, 34° 11′ N; 1071 m elev.) on Pullman (fine, mixed, superactive, thermic, Torretic Paleustolls) clay loam and Olton (fine, mixed, superactive, thermic, Aridic Paleustolls) loam soils with moderately slow permeability. The Experiment station is located on relatively flat plains (with 0.5–1.5% slope) that are interrupted by depressions forming playa lakes. Our experiment was conducted at the beginning of one of these depressions on land sloping towards the playa lake. The experiment site was irrigated by a Low Energy Precision Application center pivot system (LEPA) (Lyle and Bordovsky, 1981). In 1998, the experiment was conducted on 2.7 ha consisting of 28 differentially geo-referenced locations (DGPS) (Satloc Precision GPS Applications, Model SLX, Scottsdale, AZ) (Fig. 1a) and in 1999 the site was increased in area to 4.3 ha with 33 DGPS locations (Fig. 1b).

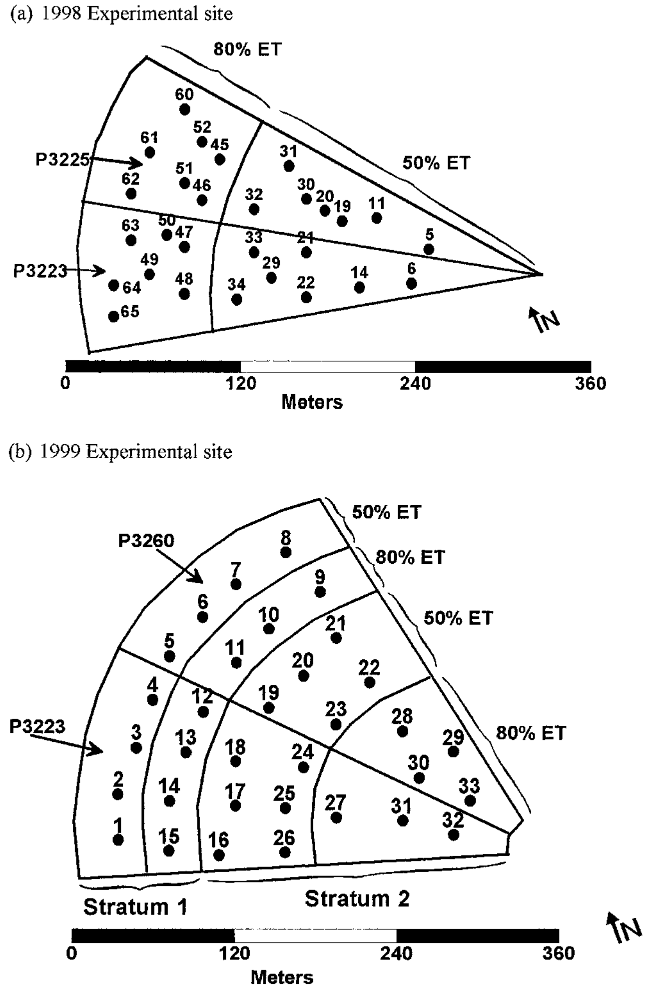

Fig. 1. Experimental sites at Halfway, TX, showing DGPS locations, water, and hybrid treatments for (a) 1998 and (b) 1999.

Treatments

The effect of water on plant growth was evaluated by imposing two irrigation regimes based on potential evapotranspiration (ET) and a site-specific crop coefficient (Bordovsky, personal communication, 1998). In each year, about half the experimental site was irrigated on the basis of 50% ET (low water) and the other half on 80% ET (high water) (Fig. 1a, b). The study area was not stratified in 1998 because we were interested in the spatial variation of grain yields across the field as influenced by the inherent variation in soil physical conditions. Because the uppermost areas, covering about 25% of the experimental area, were exclusively under 80% ET, and the lowest areas, covering 20% of the total experimental area, were exclusively under 50% ET in 1998, we decided to stratify the study area so that each water treatment was represented in both upper and lower slopes in 1999. The irrigation treatments were randomly allocated to each stratum (Fig. 1b). In 1998, two Pioneer (Pioneer Hi-Bred Int. Inc., Des Moines, IA) corn hybrids, P3223 and P3225, were grown under both high and low water treatments. On the basis of previous studies, P3223 is a drought tolerant hybrid and P3225 is a drought susceptible hybrid (Archer, personal communication, 1998). In 1999, the hybrid P3225 went out of production and was replaced by P3260, another drought susceptible Pioneer hybrid (Archer, personal communication, 1998).

Sampling Procedures

The field was characterized by measuring elevation, soil texture, soil NO_3-N, and soil moisture. Elevation measured by our GPS unit was not accurate. Therefore, we measured relative elevation at each DGPS location by direct leveling with standard field surveying instruments (David White Instruments, Model 8114, Realist Inc., Menomonee Falls, WI) using the center of the LEPA as the reference point. The center of the LEPA was assigned an arbitrary elevation of 30 m to avoid negative slopes in areas lower than the base, which would occur when if we started off with 0. Areas with elevation >33.3 m will be referred to as upper slopes and those below as middle slopes. The lowest slopes that are part of the playa lake were not cultivated. Soil texture values at 0- to 15-, 15- to 30-, 30- to 60-, and 60- to 90-cm soil depths were determined by the hydrometer method (Gee and Bauder, 1986) at all DGPS locations. A soil index (SI) was developed to represent a single measure of soil texture and was calculated as the sum of the products of percent soil texture classes and their respective water holding capacities (Machado et al., 2000). A high SI indicates a high percentage of clay and silt fractions while a low index represents sandier soils. It follows that soils with high SI have high water holding capacity (Brady, 1974). Before each planting, soil was sampled at depths similar to soil texture samples at all DGPS locations and analyzed for soil NO_3-N (AutoAnalyzer II, Technicon Industrial Systems, Tarrytown, NY). Soil moisture was monitored in the 0- to 30-, 30- to 60-, 60- to 90-, 90- to 120-, and 120- to 180-cm depths at all the DGPS locations every 2 wk with a neutron attenuation probe (CPN Model 503-DR, Martinez, CA) calibrated for these soils. Total plant water use was calculated as the sum of the differences between moisture readings at successive sampling times after including rain and irrigation amounts.

Two weeks after emergence of corn, plant populations were determined by counting the number of plants along 5 rows, 3.9 m long, centered at each DGPS location. Plant growth analysis was synchronized with soil moisture measurements. Five plants around each DGPS point were randomly sampled and transported to a laboratory where plant height, leaf number, leaf area, leaf dry matter (LDM), stem dry matter (SDM), and ear dry matter (EDM) were determined. Plant height was determined by measuring the distance between the crown and the tip of the longest leaf or tassel. Leaf number was determined by counting the number of all leaves out of fully expanded leaves. After plant height and leaf number determinations, the plant was separated into leaves, stems, and ears. Leaf area was determined by running all the leaves through a leaf area meter (LI-3100, LI-COR Inc., Lincoln, NE), and leaf area index (LAI) was calculated as leaf area per unit soil area (Brown, 1984). Leaves, stems, and ears were then oven dried separately in a draft-forced oven at 80 to 90°C to constant mass to obtain LDM, SDM, and EDM. Total plant dry matter (TDM) was the sum of LDM, SDM, and EDM. Using these data, we calculated crop growth rate (CGR) and net assimilation rate (NAR) (Brown, 1984). The CGR (g/unit area/day) was calculated as the change in TDM per day by means of the following equation:

$$\mathrm{CGR} = \frac{W_2 - W_1}{\mathrm{SA}(t_2 - t_1)} \quad [1]$$

where W_1 and W_2 are TDM in g at the beginning and end of an interval, t_1 and t_2 are the corresponding days, and SA is the soil area in m^2 occupied by the plants at each sampling. Because the 1998 season was much hotter than the 1999 season, CGR calculations based on time (d) may not be appropriate (Russelle et al., 1982). Differences in air temperature between the two seasons may confound growth analysis comparisons. We therefore modified Eq. [1] to calculate CGR on the basis of degree days (°C d) as follows:

$$\mathrm{CGR} = \frac{W_2 - W_1}{\mathrm{SA}(\mathrm{dd}_2 - \mathrm{dd}_1)} \quad [2]$$

where dd_1 and dd_2 are °C d at the beginning and end of a sampling interval. The CGR reported in this paper is based on Eq. [2]. Degree days were calculated as follows:

$$°\mathrm{C}d = \left\{\left[\frac{(T_{\max} + T_{\min})}{2}\right] - T_{\mathrm{B}}\right\} \times D \quad [3]$$

where $T_{\max}$ is the maximum daily air temperature (°C), $T_{\min}$ is the minimum daily air temperature (°C), T_B is the base temperature equal to 8°C, and D is days. The CGR can also be expressed by the following equation:

$$\mathrm{CGR} = \mathrm{NAR} \times \mathrm{LAI} \quad [4]$$

Using Eq. [4], measured LAI values, and calculated CGR values from Eq. [2], NAR (rate of dry matter increase per unit leaf area per °C d) was calculated as:

$$\mathrm{NAR} = \frac{\mathrm{CGR}}{\mathrm{LAI}} \quad [5]$$

In 1998, there was an outbreak of common smut and spider mites [*Oligonychus pratensis* (Banks)]. Common smut reduces grain yield by infecting and destroying developing grain (White, 1999). Spider mites damage leaf cells and reduce grain yield by killing leaves. Damage from common smut was rated by counting the number of infected plants out of 10 plants in a row centered at each DGPS location. Spider mite damage was determined by the method of Chandler et al. (1979). Plant lodging, observed in 1999, was assessed by counting the number of plants that had fallen in 5 rows (of 10 consecutive plants each) centered at each DGPS location. Lodging was considered root lodging if the roots failed to anchor the plants. If the stem broke above the crown, then plant stems of the lodged plants were split to determine the cause of lodging. If tunneling and girdling were evident, then southwestern corn borer (*Diatraea grandiosella* Dyar) was assumed to have caused the lodging (White, 1999). Common rust (*Puccinia sorghi* Schwein.) was also detected in 1999 and the damage was rated on a 1-to-5 scale. The rating was assigned 1 when no infection was present and 5 when >80% of the plant was covered with rust lesions. A combine fitted with a grain yield monitor (John Deere Greenstar, Dallas, TX) was used to harvest the crop.

Data Analysis

Geo-referenced grain yield data were converted to grid maps by means of a combination of MapInfo Professional (Version 5.0, MapInfo Corporation, Troy, NY) and SoilRx (Version 1.3.2.1, Red Hen Systems, Fort Collins, CO) mapping software. Grain yield data corresponding to the DGPS sampling locations were then extracted from the grid map by MapInfo Professional query. Associations of grain yields at DGPS locations with measured soil, plant, arthropod, and disease factors were determined by Pearson correlations, cluster analysis, and standard least squares.

Cluster Analysis

To determine whether we can predict grain yields from plant growth, we first identified grain yield clusters or areas with more or less homogeneous, but distinct grain yields (Fig. 2a, b). Data on plant growth analyses in each cluster were then analyzed and matched to the final grain yield patterns. Ward's Method, a hierarchical clustering procedure, was used to identify grain yield clusters in this experiment (JMP, SAS Institute, 1989–1997). Hierarchical clustering starts with each point in its own cluster. At each successive step, two clusters that are closest to each other are joined and the process continues until distinct clusters are obtained. The Ward Method distance between two clusters is the sum of squares between the two clusters summed over all the factors. At each generation, within-cluster sum of squares is minimized over all partitions obtainable by merging two clusters from the previous generation (JMP, SAS Institute, 1989–1997). An unbalanced

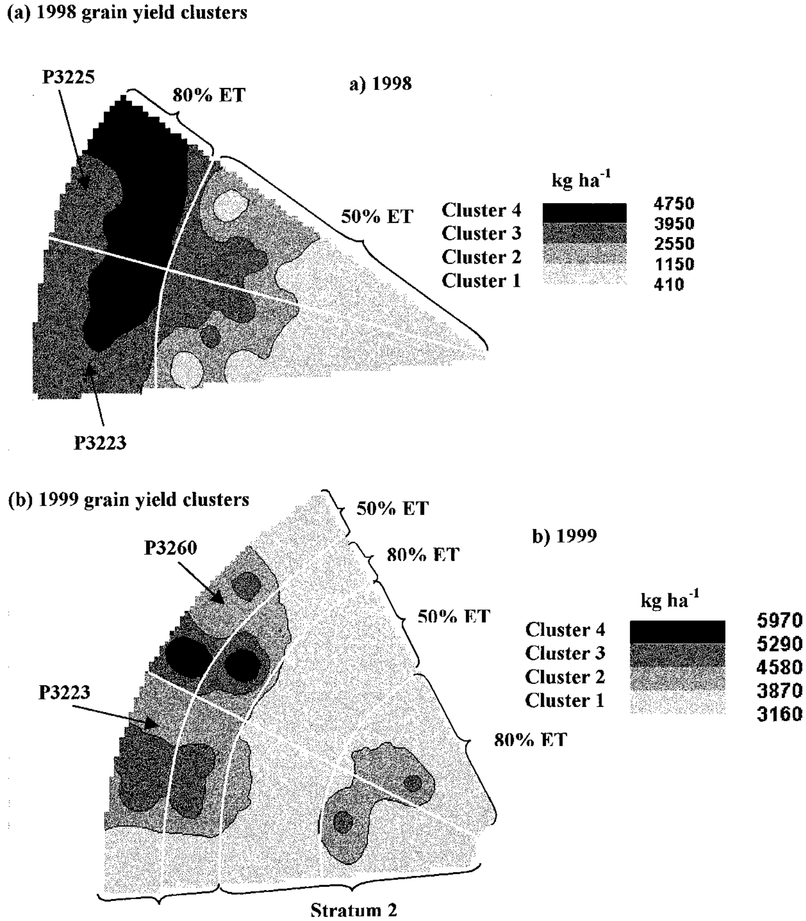

Fig. 2. Grain yield clusters in (a) 1998 and (b) in 1999 at Halfway, TX.

design was used to compare growth patterns and other factors influencing grain yields among clusters (JMP, SAS Institute, 1989–1997).

RESULTS AND DISCUSSION

Grain Yield Clusters

Because there were statistically no significant differences in grain yield between the two hybrids under both water treatments, only irrigation effects on the measured parameters will be discussed. Using the plot of distance and curvature between clusters, we identified four significantly different grain yield clusters in 1998 and 1999 (Fig. 2, 3a, b). The clusters were named 1, 2, 3, and 4 with Cluster 1 representing areas with the lowest grain yield and Cluster 4 with the highest grain yield. In 1998, grain yields varied considerably (CV%=63) ranging from 276 to 6399 kg ha^{-1}. In 1999, grain yields were less variable (CV% = 24) and ranged from 2028 to 6253 kg ha^{-1}. In 1998, demarcation of clusters was largely influenced by the water treatments. The 1998 growing season was hot and dry and substantial grain yield differences due to water treatments were expected. Clusters 1 and 2 covered 43% of the area and were located under the low water treatment, whereas Clusters 3 and 4 covered the remaining 57% of the area. Cluster 4 was exclusively under the high water treatment but part of Cluster 3 (7% of area) was under the low water treatment (Fig. 2a). In 1999, clusters were not influenced by the water treatment. The 1999 growing season received more rain than the 1998 season and the frequency of rainfall in 1999 made it impossible to impose water treatments early in the season. Cluster 1 covered 62% of the area and occupied areas under both low and high water treatment (Fig. 2b). Cluster 2 also occupied areas under both water treatments and covered 24% of the experimental area. Combined, the two clusters represented 86% of the total land area. The remaining 14% of the area was divided between Clusters 3 and 4. More rainfall reduced the spatial variation in grain yield in 1999.

Factors Affecting Grain Yields of Clusters

Elevation, SI, and Soil NO_3-N

In 1998, grain yield clusters followed trends in elevation with Clusters 1 and 2 occupying the middle slopes and Clusters 3 and 4 occupying upper slopes (Table 1). The SI in the 0- to 90-cm soil depth profile also followed the trends in elevation suggesting that soils in the middle slopes (Cluster 1 and 2) were lighter (higher sand fraction) than soils in the upper slopes (Cluster 3 and 4) (higher clay and silt fractions) (Table 1). Of the soil depth sampled, only SI in the 0- to 15-cm depth profile was not significantly different among the clusters (Table

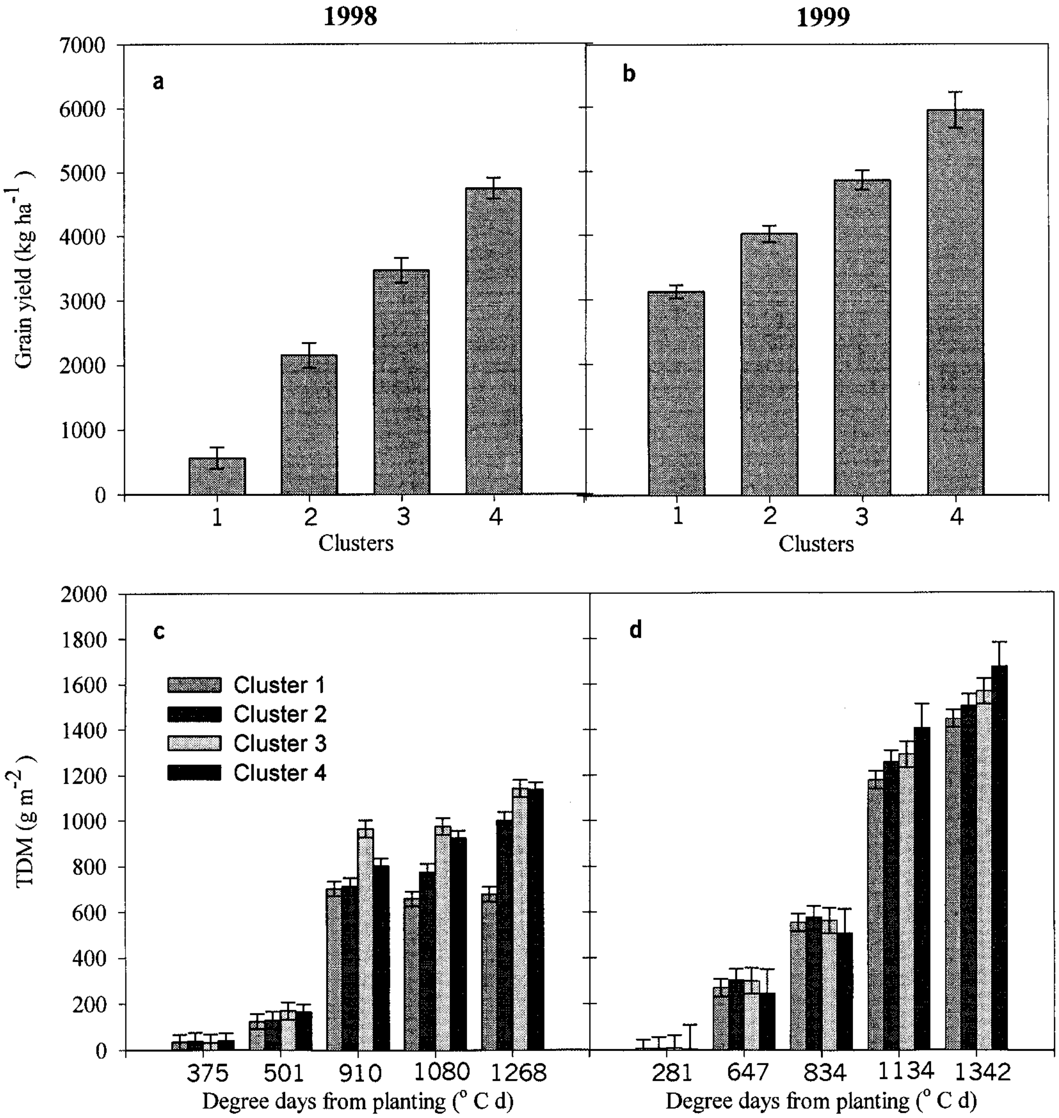

Fig. 3. Corn grain yield clusters and total plant dry matter (TDM) accumulation in each cluster in 1998 and 1999. The bars represent standard errors for each cluster.

1). Elevation and SI respectively, explained 53 and 49% of grain yield variation. Grain yields were high in the upper slopes and in areas with high SI. Soil NO_3-N (0–90 cm) explained about 29% of grain yield variation. Grain yields were lowest in Cluster 1 where the soil NO_3-N was highest. It appears the crop in Cluster 1 could not utilize the soil NO_3-N, probably because of drought stress.

In 1999, there were no significant differences in elevation and SI among the clusters (Table 2). Since the clusters were based on grain yields, it follows that elevation and SI were not the dominant factors influencing grain yields in 1999. This was probably due to more seasonal moisture during this year than in 1998. Similar work also indicated that topographic effects limiting crop yields in drought years are minimized in seasons with adequate water (Halvorson and Doll, 1991; Fiez et al., 1995; Kravchenko and Bullock, 2000). In 1999, soil NO_3-N (0–90 cm) was positively correlated with grain yields (r = 0.48) and was highest in Cluster 4 where the highest grain yields were observed (Table 2). Soil NO_3-N, therefore, positively influenced grain yields when water was adequate.

Plant Water Use

In 1998, plant water use was 26% higher in Clusters 3 and 4 that were mostly under 80% ET than in Clusters 1 and 2 that were mostly under 50% ET (Table 1). Water treatments strongly influenced the differences in water use patterns. Total amount of water (applied and rain) received under the high and low water treatments was 485 and 326 mm, respectively. Furthermore, water use in Cluster 2 was significantly higher than in Cluster 1 (Table 1). High water use in Cluster 2 could be attributed to higher SI observed in this cluster than in Cluster 1. Water use was positively correlated with SI (r = 0.54) probably because the water holding capacity of the soil increased with SI. Water use explained 55% of grain yield variation during 1998. In 1999, there were no signif-

Table 1. Comparison of measured factors among grain yield clusters in 1998.

	Grain yield clusters					
Factor	Cluster 1	Cluster 2	Cluster 3	Cluster 4	SE	LSD 5%
Elevation (32 m)	32.72a†	33.15b	33.43b	33.49c	0.10	0.32
Soil index (0–90 cm)	18.83a	19.65b	20.23bc	20.59c	0.25	0.79
Soil index (0–15 cm)	19.15	19.78	18.73	19.14	0.26	ns
Soil index (15–30 cm)	19.77ac	20.61b	19.67a	20.41bc	0.24	0.75
Soil index (30–60 cm)	18.55a	19.86b	21.36c	21.21c	0.38	1.21
Soil index (60–90 cm)	18.47a	18.90a	20.12b	20.77b	0.35	1.13
Electrical conductivity (0–30) (mS m^{-1})	19.30	20.80	23.53	24.05	2.07	ns
Electrical conductivity (0–90) (mS m^{-1})	23.55	24.22	19.82	21.91	1.31	ns
Depth to caliche (cm)	55.58	64.22	59.33	85.61	15.10	ns
Soil pH (0–90 cm)	7.66	7.59	7.54	7.63	0.05	ns
Soil NO_3-N (kg ha^{-1}) (0–90 cm)	70.98a	49.23b	52.06b	42.01b	5.79	18.42
Soil NO_3-N (kg ha^{-1}) (0–15 cm)	9.77	9.75	8.59	6.64	1.04	ns
Soil NO_3-N (kg ha^{-1}) (15–30 cm)	11.22	9.57	8.72	7.06	1.08	ns
Soil NO_3-N (kg ha^{-1}) (30–60 cm)	21.13	15.60	18.56	15.40	1.75	ns
Soil NO_3-N (kg ha^{-1}) (60–90 cm)	28.86a	14.31b	16.19ab	12.91b	4.46	14.19
Water use (cm)	18.29a	20.24b	25.88c	26.05c	0.95	3.03
Plants ha^{-1}	48 618	49 997	53 127	50 100	1 226	ns
Ears ha^{-1}	32 741a	42 748b	51 089c	51 398c	1 688	5 370
Ears $plant^{-1}$	0.68a	0.86b	0.97c	1.02c	0.03	0.10
Spider mite damage	2.12	2.08	2.53	1.67	0.22	ns
Common smut	5.41a	3.62b	2.32b	2.04b	0.54	1.71
Leaf firing	5.00a	1.67b	4.17a	0.63b	1.17	3.72
Leaf senescence	2.63	2.67	2.17	2.00	0.25	ns

† Means followed by the same letter across the clusters are not significantly different at $P < 0.05$.

Table 2. Comparison of measured factors among grain yield clusters in 1999.

	Grain yield clusters					
Factor	Cluster 1	Cluster 2	Cluster 3	Cluster 4	SE	LSD 5%
Elevation (32 m)	32.86	33.27	33.19	33.52	0.23	ns
Soil index (0–90 cm)	19.61	20.18	19.90	21.14	0.51	ns
Soil index (0–15 cm)	18.99	19.56	18.87	19.72	0.42	ns
Soil index (15–30 cm)	19.95	20.73	20.04	21.27	0.62	ns
Soil index (30–60 cm)	19.83	20.44	20.46	21.47	0.72	ns
Soil index (60–90 cm)	19.54	19.97	19.77	21.46	0.56	ns
Soil NO_3-N (kg ha^{-1}) (0–90 cm)	142.32a†	156.35a	152.50a	437.90b	25.51	81.16
Soil NO_3-N (kg ha^{-1}) (0–15 cm)	41.01a	50.00a	48.99a	140.28b	6.51	20.73
Soil NO_3-N (kg ha^{-1}) (15–30 cm)	26.70a	33.91a	31.41a	88.54b	7.53	23.96
Soil NO_3-N (kg ha^{-1}) (30–60 cm)	35.87a	41.56a	40.94a	122.55b	10.63	33.82
Soil NO_3-N (kg ha^{-1}) (60–90 cm)	38.75a	30.87a	31.16a	86.54b	7.70	24.51
Water use (cm)	45.75	43.90	44.06	44.79	1.70	ns
Plants ha^{-1}	40 294	40 635	42 431	40 772	1 662	ns
Ears ha^{-1}	150 285	149 987	164 190	147 027	15 772	ns
Ears $plant^{-1}$	3.71	3.69	3.83	3.60	0.306	ns
Leaf common rust	1.66	1.93	2.69	1.25	0.38	ns
Southwestern corn borer	2.91	2.36	2.77	2.40	0.25	ns
Plant lodging (%)	1.99	1.91	1.89	2.20	0.29	ns
Leaf senescence (%)	6.36	5.76	5.14	4.70	0.55	ns

† Means followed by the same letter across the clusters are not significantly different at $P < 0.05$.

icant differences in the water use among all clusters (Table 2) suggesting that variations in water use did not affect variations in grain yield during this year. High and low water treatments, respectively, received totals of 526 and 396 mm, representing an increase of 8 and 17% over 1998 amounts.

Arthropods and Diseases

In 1998, there was an outbreak of spider mites and common smut (Table 1). There were, however, no significant differences in the spider mite damage among the clusters. Common smut damage was highest in Cluster 1 (Table 1) where the fungus explained 60% of the reduction in grain yields. Drought stress conditions that prevailed in Cluster 1 were conducive for the development of the fungus (White, 1999). Common smut damage was not significantly different among Clusters 2, 3, and 4. Leaf firing was significantly higher in Clusters 1 and 3 than in Cluster 2 and 4. This was probably because Clusters 1 and 3 had more border area exposed to hot dry air than Clusters 2 and 4 whose areas were mostly flanked by Clusters 1 and 3 (Fig. 1).

In 1999, there were no significant differences in plant damage due to leaf common rust, southwestern corn borer, plant lodging, and leaf senescence among the clusters (Table 2).

Growth Analysis

Elevation, SI, soil NO_3-N, water use, and common smut clearly influenced grain yield clusters. Effects of these factors are likely to show in plant growth patterns. Information required to improve management of SSF can, therefore, be obtained through plant growth monitoring. The results of comparisons of crop growth patterns in grain yield clusters are presented below. Because we sampled plants on the basis of time (not stages), there are slight differences in growth stages at the time of sampling between the two years, particularly during the vegetative phases.

Total Plant Dry Matter

In 1998, TDM from 0 (emergence) to 501°C d (~12-leaf stage) did not differ significantly among grain yield clusters (Fig. 3c). From 501 to 910°C d (~silking), TDM in Clusters 3 and 4 increased significantly more than in Clusters 1 and 2. After silking, TDM continued to increase in all of the clusters except Cluster 1. On average, TDM reached a maximum of 991 g m^{-2} at 1268°C d (~dent stage). The differences in TDM among clusters were in line with the differences in grain yield clusters. The TDM explained 44% of grain yield variation in 1998.

In contrast, there were no significant differences in TDM among clusters from 0 (emergence) to 834°C d (~silking) in 1999 (Fig. 3d). The TDM increased rapidly from 834 to 1134°C d (~dough stage), and during this period, the TDM in Clusters 3 and 4 were significantly higher than TDM in Cluster 1. Clusters 1 and 2 did not differ significantly in TDM. Differences in TDM among clusters observed during this period were also observed at 1342°C d (~dent). Although TDM variations matched variations in grain yield clusters during the dough and dent stages in 1999, only 9% of grain yield variation could be explained by TDM. On average, TDM reached a maximum of 1548 g m^{-2} at dent, an increase of 35% from 1998.

Partition of Dry Matter among Organs

In 1998, LDM reached a maximum of 210 g m^{-2} at the silking stage (Fig. 4). Differences in LDM that matched differences in grain yields began to show at the 12-leaf stage but only LDM in Cluster 1 was significantly lower than LDM in Cluster 3 (Fig. 4). By silking, differences in LDM had increased and matched patterns in grain yield clusters except LDM in Cluster 4, which increased slowly. At the dough stage, the LDM in Clusters 3 and 4 was significantly higher than the LDM in Clusters 1 and 2. The LDM in Clusters 1 and 2 did not change in the period from dough to dent stages, suggesting that there was little or no demand for assimilates in these clusters in this period. Reduced demand for assimilates in these clusters could be attributed to drought stress conditions, which probably reduced ear size and favored common smut infection that destroyed kernels. The LDM in Clusters 3 and 4 decreased significantly during the same period indicating that some translocation of assimilates from the leaves to the grain took place. In 1999, LDM in all clusters reached a similar maximum (210 g m^{-2}) at 1134°C d (Fig. 4b) and it was only at this stage that significant differences in LDM matched differences in grain yield clusters. At this stage, the LDM in Cluster 1 was lower than LDM in other clusters. The LDM in Clusters 2, 3, and 4 were not significantly different from each other. The increase in LDM during the grain filling period indicated that leaves produced assimilates in excess of grain filling requirements and continued to accumulate dry matter. This could be attributed to favorable climatic conditions and high soil moisture in 1999.

On average, SDM reached a maximum of 418 g m^{-2} at silking in 1998 and had declined by 26% at dent (Fig. 4c). The decline in SDM indicates dry matter that contributed to grain filling. Patterns in SDM did not match patterns in grain yield clusters except at the dough stage. In contrast, in 1999, the SDM in all the clusters reached a maximum of 470 g m^{-2} at the dough stage and declined by only 4% at dent (Fig. 4d). The increase in SDM during the grain filling period suggests that SDM did not contribute to grain filling, but probably accumulated excess dry matter from the leaves. The SDM matched grain yield clusters at the dough and dent stages but the differences in SDM were significant at the dough stage. At this stage, SDM in Cluster 1 was significantly lower than SDM in Cluster 4. The SDM of Cluster 2 and 3 were not significantly different from each other and to either SDM in Cluster 1 or 4.

The EDM followed trends in grain yield clusters in both years (Fig. 4e, f). Differences in EDM, however, were more pronounced in 1998 than in 1999. In 1998, EDM reached a maximum of 395 g m^{-2} at dent. The EDM in Clusters 3 and 4 was significantly higher than in Clusters 1 and 2. Differences in EDM were evident at silking, before the start of rapid grain filling, indicating that ear development was affected by drought stress during the early phases of the reproductive stages. The differences in EDM increased further during grain filling where a combination of drought stress and common smut infestation significantly reduced EDM in Cluster 1. In 1999, the EDM at silking was not significantly different among clusters, suggesting that growing conditions prior to silking were not detrimental to EDM accumulation. The 1999 season was cooler and wetter than the 1998 season in this period. Significant differences in EDM were only observed between Cluster 1 and 4 at the dough and dent stages. These differences were in line with the differences in grain yield clusters. The EDM reached a maximum of 903 g m^{-2} at the dent stage in 1999, which was 56% more than in 1998.

Crop Growth Rate

In 1998, CGR in all four clusters increased from emergence to a peak at the silking stage and then declined (Fig. 5a). On average, CGR reached a maximum of 1.6 g m^{-2} °C d^{-1} (23 g m^{-2} d^{-1}), which is less than half the CGR (51 g m^{-2} d^{-1}) that has been reported for corn (Brown, 1984). No significant differences in CGR were observed among the clusters before silking. At silking, CGR in Cluster 4 was significantly higher than CGR in the other clusters. The considerable reduction in CGR measured from silking to dough stage was probably due to the reduction of solar radiation during the periods preceding these dates (Machado et al., 2000). The reduction in CGR could have increased remobilization of assimilates from both leaves and stems for grain filling causing the reduction in SDM.

The CGR was influenced by NAR (r = 0.92) more

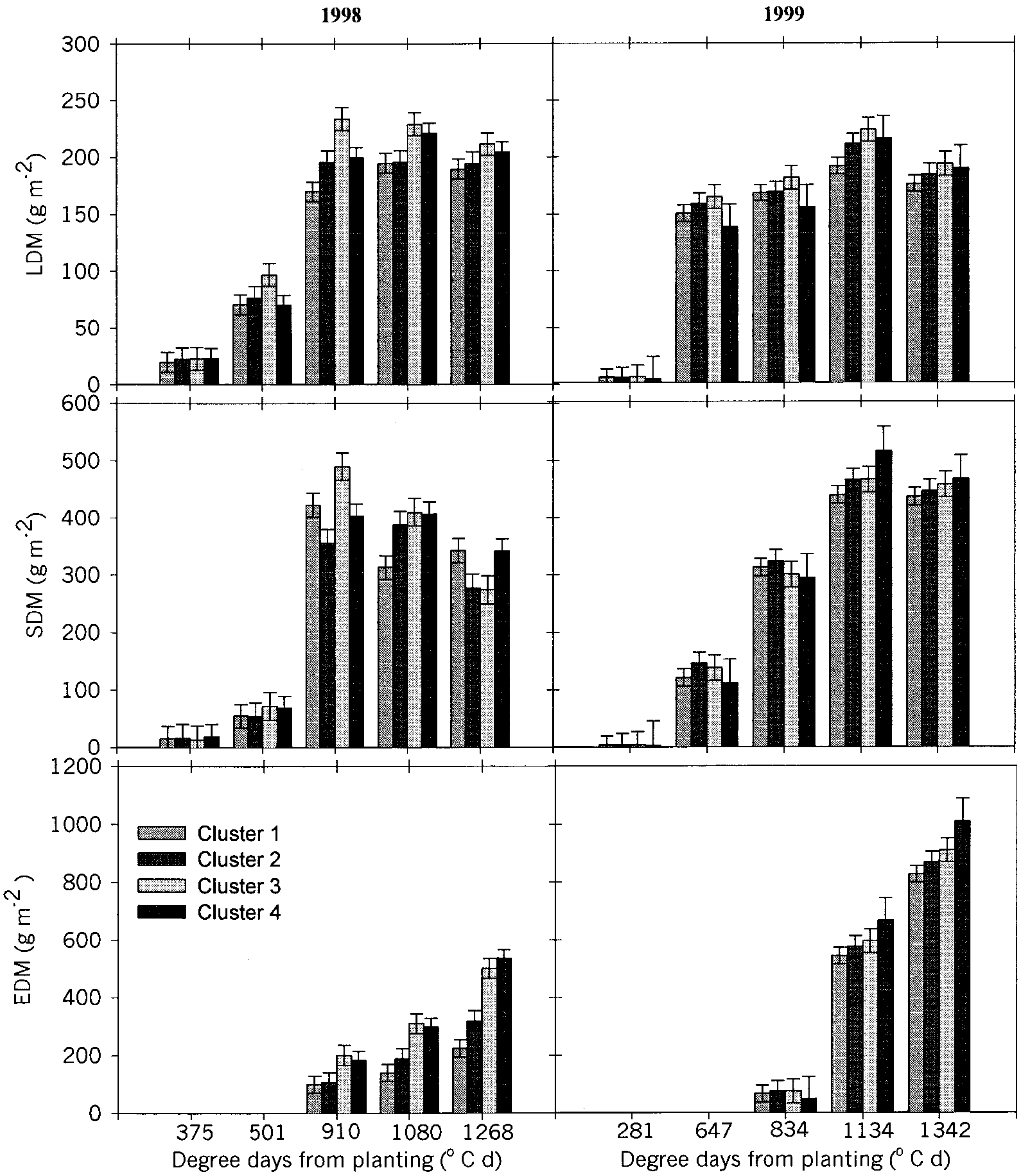

Fig. 4. Leaf dry matter (LDM), stem dry matter (SDM), and ear dry matter (EDM) accumulation in corn in each cluster in 1998 and 1999. The bars represent standard errors for each cluster.

than by LAI ($r = 0.46$). The NAR followed CGR trends (Fig 5b) and reached an average maximum of 0.7 g m^{-2} °C d^{-1} at the 12-leaf stage. At this stage, NAR in Clusters 3 and 4 was significantly higher than NAR in Clusters 1 and 2 (Fig. 5b). The differences in NAR were in line with differences in water treatments. No differences in NAR was observed between either Cluster 1 and 2 under the low water treatment or between Cluster 3 and 4 under the high water treatment. The period leading to the 12-leaf stage is critical in the management of corn. During this period, the plant begins a rapid increase in nutrient and dry matter accumulation. Around the 12-leaf stage, the ovule number and ear size are being determined and any moisture stress or nutrient deficiencies can reduce the potential number of seeds and size of the ear harvested (Ritchie et al., 1993). It is probably during this period that drought stress affected ear development, which resulted in the low EDM observed at silking in clusters under low water treatment in 1998. On average, grain yields were correlated to both CGR ($r = 0.67$) and NAR ($r = 0.57$) at the 12-leaf stage.

There were no significant differences in LAI from 8- to the 12-leaf stages among clusters (Fig. 5c). The LAI in Clusters 1, 2, and 3 reached a peak in the period from the 12-leaf stage to silking, while the LAI in Cluster 4 developed slowly and peaked between 910 and 1080°C d. Mean maximum LAI obtained in this year was 2.5. At dough stage, LAI in Cluster 3 and 4 was significantly higher than LAI in Cluster 1 and 2. The differences in LAI at this stage were in line with differences in water treatments but no differences in LAI were observed between either Clusters 1 and 2 under the low water treatment or between Clusters 3 and 4 under the high

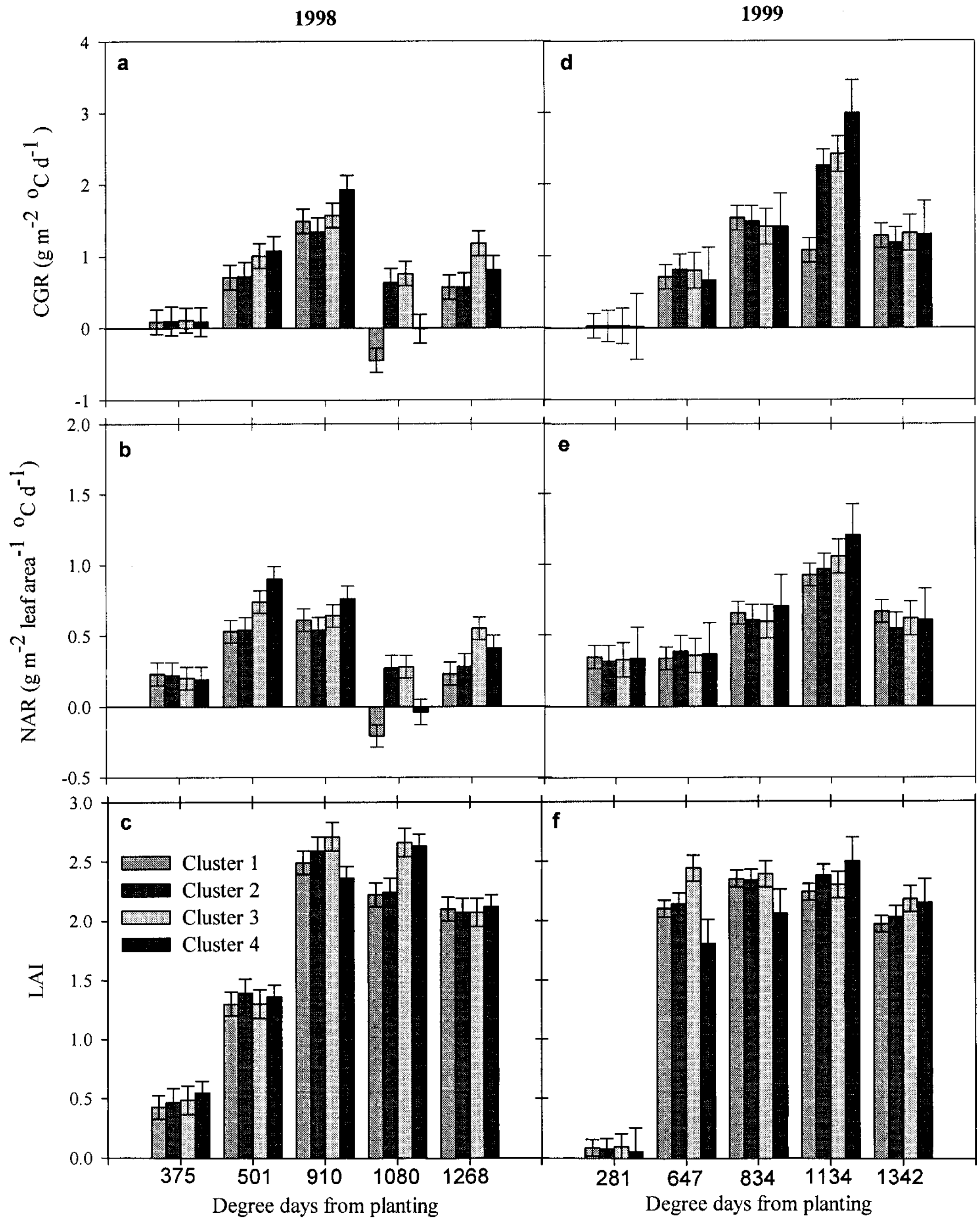

Fig. 5. Crop growth rate (CGR), net assimilation rate (NAR), and leaf area index (LAI) of corn grain yield clusters in 1998 and 1999. The bars represent standard errors for each cluster.

water treatment. There were no differences in LAI among clusters at the dent stage.

In 1999, CGR reached a maximum rate of 2.4 g m^{-2} °C d^{-1} (32 g m^{-2} d^{-1}) during the period from silking to dough stage in all clusters (Fig. 5d). Although the maximum CGR increased by 35% from 1998, it was still 63% of the CGR reported for corn (Brown, 1984). The high CGR during grain filling led to the continued growth of both leaves and stems (Fig. 4b, d). The CGR was not significantly different among clusters during the vegetative growth period, suggesting that there was no drought stress experienced by the crop in all clusters during this period. Differences in CGR occurred only during the period from silking to the dough stage when the CGR in Clusters 1 and 2 became significantly lower than CGR in Cluster 4. The CGR in Cluster 3 was not significantly different from CGR in Cluster 4. The CGR in all clusters decreased significantly in the period from dough to dent probably because of reduced assimilate demand. The NAR followed trends in CGR, reaching a maximum of 1.0 g m^{-2} °C d^{-1} at the dough stage. There were, however, no significant differences in NAR at all sampling dates (Fig. 5e). The LAI in Cluster 3 reached a peak at 647°C d (15-leaf stage) while the LAI in Cluster 2 and 3 reached a peak at the silking stages (Fig. 5f). In Cluster 4, the LAI developed significantly

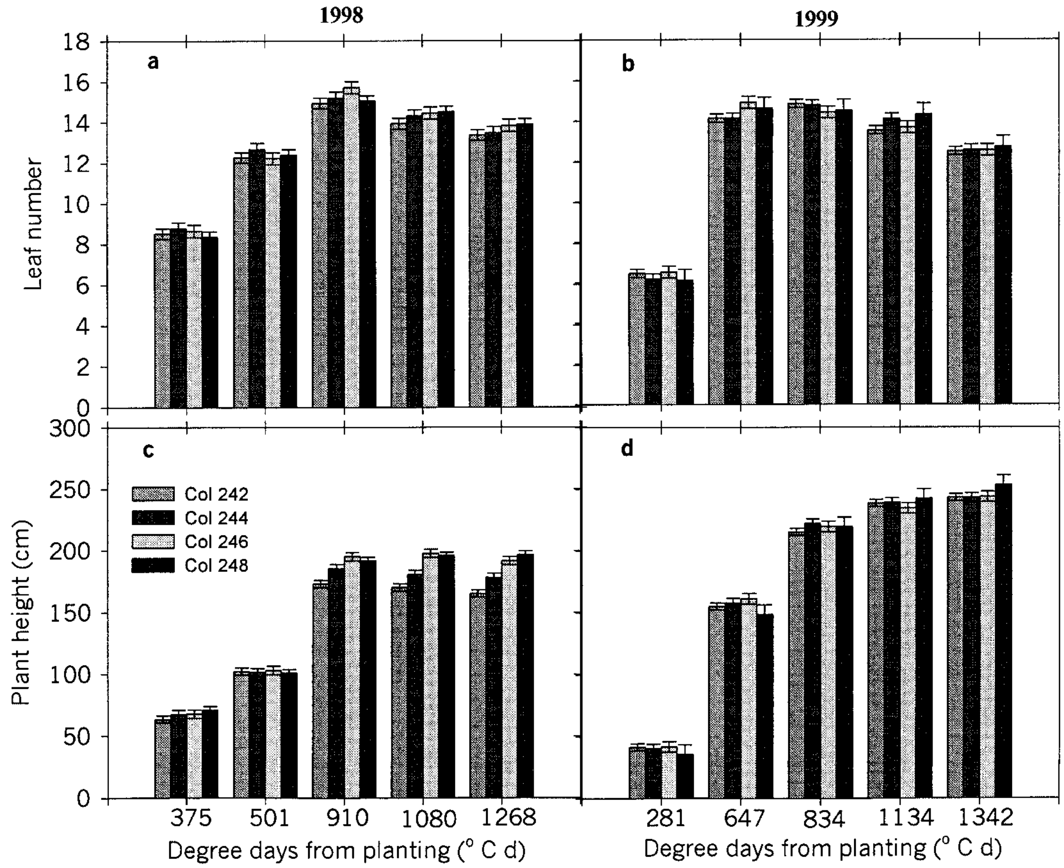

Fig. 6. Leaf number and plant height of corn in each grain yield cluster in 1998 and 1999. The bars represent standard errors for each cluster.

slower than in all the clusters and reached the maximum between 834 and 1134°C d. Patterns in LAI at all sampling dates did not match patterns in grain yield clusters. Maximum LAI values were similar to 1998 and reached 2.4 at the silking stage.

Leaf Number

In 1998, leaf number per plant reached a maximum of about 15 during silking and dropped to about 13 at dent (Fig 6a). There were, however, no significant differences in the number of leaves per plant among all clusters at all sampling times except at dough stage. At this stage, leaves per plant in Cluster 1 were significantly lower than in Cluster 4. In 1999, leaf numbers in Cluster 3 and 4 reached the maximum at the 15-leaf stage and plants in Cluster 1 and 2 produced the maximum number of leaves at silking (Fig. 6b). The leaf numbers declined steadily thereafter but remained above 12 at dent. Patterns in leaf number did not match patterns in TDM or in grain yield clusters.

Plant Height

Plant height increased to a peak of 186 cm at silking in all clusters in 1998 (Fig 6c). No significant differences in plant height were found among the clusters in the period from emergence to the 12-leaf stage. From the 12-leaf stage to the dent stage, the plant height in Cluster 3 and 4 was significantly higher than in Cluster 1 and 2. Plants in Cluster 2 were also significantly taller than plants in Cluster 1 during the same period. Plant height explained 90% and 61% of the variations in TDM and grain yield, respectively. In 1999, plant height in all clusters reached a maximum of 245 cm at dent (Fig. 6d), a 24% increase from 1998. There were no significant differences in plant height among the clusters at all stages of plant growth except at the 15-leaf stage where the plant height in Cluster 4 was significantly less than the plant height in Cluster 3. During this year, trends in plant height did not follow the trends in either TDM or match patterns in grain yield clusters.

Plants per Hectare, Ears per Plant, and Ears per Hectare

There were no significant differences in the number of plants per hectare among the clusters in both years indicating that plant population did not influence grain yield. The ears per plant and ears per hectare, however, were significantly lower in Clusters 1 and 2 than in Clusters 3 and 4 (Table 1) in 1998. This supports the conclusion that ear numbers and size were affected by drought stress that was imposed in these clusters. The finding that ears per plant and ears per hectare were significantly higher in Cluster 2 than in Cluster 1 also suggest that the effect of drought stress was exacerbated by the low water holding capacity of the low SI soils found in Cluster 1. In 1999, ears per plant and ears per hectare were not significantly different among clusters (Table 2).

Implications for SSF

Dry and hot conditions in 1998 increased spatial variability in corn grain yields when compared with 1999. Effects of drought in 1998 were reflected in low biomass, plant height, CGR, NAR, and grain yield measurements. During this year, trends in grain yield clusters followed trends in elevation, SI, and water use. In contrast, the influence of elevation and SI on grain yield diminished in 1999, which was wetter and cooler than 1998. Arthropods and diseases and their effects on grain yield also changed with season. Common smut and spider mites incidences in 1998 were substituted by leaf common rust and southwestern corn borer outbreak in 1999. These findings have great implications on the management of SSF. On the basis of our results, SSF practices that are based on soil physical characteristics are likely to be intensified under drought or stressful conditions than under nonstressful conditions. Great improvements in the management of SSF will, however, be achieved when the effects of soil physical and chemical factors, water, pests, and diseases on crop yields can be integrated and evaluated as a system. Growth analysis provides an excellent opportunity to monitor interactions of all factors affecting crop yields and opens ways to manage these factors in integrated systems.

Diagnosis of growth-limiting factors and grain yield forecasting through growth analysis should significantly improve SSF management. Our results indicated that patterns in TDM, LDM, EDM, NAR, LAI, and plant height matched patterns in grain yield clusters at some point during the two seasons and therefore reflected upon growth-limiting factors. Information on these variables can, therefore, be used to formulate management decisions for SSF. The differences in these variables among clusters were more pronounced and were observed earlier in 1998, a drier year than in 1999, a wetter year. Sadler et al. (1995) also reported that differences in phenology, biomass, leaf area, and yield components were most pronounced under drought. Effects of water, elevation, and SI showed up well in most growth analysis measurements. The differences in LDM, EDM, and TDM were apparent during the period from 12-leaf to the silking stage in 1998 and from silking to the dough stages in 1999. Early in-season management, therefore, would have been possible only in 1998, when the differences were detected early. Interventions after the 12-leaf stage may be too late to influence ear development but could ensure that the potential size of kernels and ear numbers set earlier would be realized.

Greater benefit can be realized by intervening in the period from emergence to the 12-leaf stages. It is during this period that the plants are established and the potential number of leaves and ears are initiated. Weed and some insect control are important early in the season. Later, around the 9- and 10-leaf stages, the plants grow rapidly and require nutrients and water in greater quantities. Detecting areas under which plants are not growing well during this period and intervening appropriately may increase the grain yield potential of these areas. Although biomass measurements could be used to forecast grain yields, the information they provide is obtained later in the season when management choices are reduced. Zhang et al. (1998) obtained better estimates of corn and soybean [*Glycine max* (L.) Merr.] grain yields from the Normalized Difference Vegetation Index (NDVI) obtained in July than in June because these crops had reached full cover in July. By this time, the crops were at growth stages (flowering to grain filling) when chances to affect grain yields significantly were reduced. The biomass observed at a particular point in time is the result of dry matter accumulation over time and the ensuing information may not be useful for in-season management of SSF by the time it is obtained. It is, therefore, advantageous to determine crop performance instantaneously particularly when managing factors whose effects on crop growth are not readily obvious or that have a long course of action. In 1998, NAR was the only variable that showed differences among clusters in the period from the 9- to the 12-leaf stages. Using NAR data, areas under the two watering treatments could be identified before differences in biomass-related measurements were apparent. Therefore, NAR measurements can identify areas under drought stress. The measurement of NAR, however, is not easy because it involves destructive sampling, which may not be suitable for farmers. Measurements of other physiological processes that are easy to measure and that are closely associated with NAR could solve the problem. The NAR is closely associated with photosynthesis and respiration (Hageman and Lambert, 1988; Farquhar and Sharkey, 1994). Photosynthesis is cumbersome to measure, but can be estimated from spectral vegetation or pigment indexes derived from imaging spectroscopy data (Sellers, 1987; Verma et al., 1993). Photosynthesis is also closely related to stomatal conductance, which can be assessed from canopy temperature. Actively growing, healthy crop stands usually have higher stomatal conductance and are cooler than stressed crop stands. Canopy temperature can be acquired relatively easily by infrared thermometry. A number of indexes based on air and canopy temperature have been developed for irrigation (Jackson et al., 1981). Similarly, more work can be done to adapt these indexes for pests and diseases effects. Remote sensing offers a relatively easy way to obtain information about instantaneous crop performance early in the season.

Although biomass-related measurements were obtained later than NAR, they still provided useful information for in-season management of SSF. With information on LAI, TDM, LDM, and plant height, it would have been possible to detect water stress from the 12-leaf stage to silking in 1998. Increasing the amount of water applied would have improved grain yields in affected areas. Information on EDM would have improved chances of detecting common smut damage in 1998. Scouting, however, would be a better way to detect affected areas. Knowledge of microenvironments that favor arthropod and disease incidences can greatly improve scouting efficiency. For instance, common smut preferred plants growing under drought. Spider mites preferred plants growing under both drought and high soil NO_3-N (Machado et al., 2000). Identifying microenvironments that favor arthropod and disease incidences in the field is one way to integrate biotic and abiotic factors affecting crop growth. Management of SSF as systems is possible when biotic and abiotic effects are integrated.

Information obtained from growth analysis is not only important for the immediate season but can be used for SSF management decisions in the following season. If soil physical characteristics were the causes of poor plant growth, such as low SI in Cluster 1 when compared with Cluster 2 in 1998, information obtained from growth analysis in the previous season can be used to demarcate management zones for the next season. Such information may also reduce costs of expensive soil surveys and soil texture analyses. If pests and diseases were the causes of poor plant growth, the microenvironments that favor their development should be identified. With this information, scouting costs can be reduced or disease outbreak can be prevented. For instance, scouting for common smut could be limited to areas prone to drought. Alternatively, reducing drought stress in these areas may prevent the spread of the fungus.

CONCLUSIONS

Our results indicated that growth analysis provides information on the response of plants to biotic and abiotic factors and explains grain yield variation among clusters. Potentially, all the information obtained is useful for SSF management. However, the usefulness of growth analysis is season dependent, being more informative in a drought year than in a relatively wet year. Differences in growth analysis parameters that show up early, such as NAR, can be used for in-season management, and those obtained as the season progresses, such as biomass, can be used for either in-season management or in the next season depending on when the information is obtained. The correct diagnosis of poor plant performance will determine the success of this approach. More information on the effects of the interactions between biotic and abiotic should also be obtained to improve SSF.

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