THESIS

ACTIVE SENSING: AN INNOVATIVE TOOL FOR EVALUATING GRAIN YIELD AND NITROGEN USE EFFICIENCY OF MULTIPLE WHEAT GENOTYPES

Submitted by

Mohammed Abdulridha Naser

Department of Soil and Crop Sciences

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Master's Committee:

Advisor: Rajiv Khosla

Scott Haley
Robin Reich

ABSTRACT

ACTIVE SENSING: AN INNOVATIVE TOOL FOR EVALUATING GRAIN YIELD AND NITROGEN USE EFFICIENCY OF MULTIPLE WHEAT GENOTYPES

Precision agricultural practices have significantly contributed to the improvement of crop productivity and profitability. Remote sensing based indices, such as Normalized Difference Vegetative Index (NDVI) have been used to obtain crop information. It is used to monitor crop development and to provide rapid and nondestructive estimates of plant biomass, nitrogen (N) content and grain yield. Remote sensing tools are helping improve nitrogen use efficiency (NUE) through nitrogen management and could also be useful for high NUE genotype selection. The objectives of this study were: (i) to determine if active sensor based NDVI readings can differentiate wheat genotypes, (ii) to determine if NDVI readings can be used to classify wheat genotypes into grain yield productivity classes, (iii) to identify and quantify the main sources of variation in NUE across wheat genotypes, and (iv) to determine if normalized difference vegetation index (NDVI) could characterize variability in NUE across wheat genotypes. This study was conducted in north eastern Colorado for two years, 2010 and 2011. The NDVI readings were taken weekly during the winter wheat growing season from March to late June, in 2010 and 2011 and NUE were calculated as partial factor productivity and as partial nitrogen balance at the end of the season. For objectives i and ii, the correlation between NDVI and grain yield was determined using Pearson's product-moment correlation coefficient (r) and linear regression analysis was used to explain the relationship between NDVI and grain yield. The K-means clustering algorithm was used to classify mean NDVI and mean grain yield into three classes. For objectives iii and iv, the parameters related to NUE were also calculated to measure their relative importance in genotypic variation of NUE and power regression analysis between NDVI and NUE was used to characterize the relationship between NDVI and NUE. The results indicate more consistent association between grain yield and NDVI and between NDVI and NUE later in the season, after anthesis and during mid-grain filling stage under dryland and a poor association in wheat grown in irrigated conditions. The results suggest that below saturation of NDVI values (about 0.9), (i.e. prior to full canopy closure and after the beginning of senescence or most of the season under dryland conditions) NDVI could assess grain yield and NUE. The results also indicate that nitrogen uptake efficiency was the main source of variation of NUE among genotypes grown in site-years with lower yield. Overall, results from this study demonstrate that NDVI readings successfully classified wheat genotypes into grain yield classes across dryland and irrigated conditions and characterized variability in NUE across wheat genotypes.

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SUMMARY OF CHAPTER I

Remote sensing based indices such as Normalized Difference Vegetative Index (NDVI) are sensitive to biomass and nitrogen (N) variability in crop canopies. Active remote sensing tools such as Greenseeker® can measure NDVI using light reflected from crop canopies. The objectives of this study were (i) to determine if active sensor based NDVI readings can differentiate wheat genotypes (ii) to determine if NDVI readings can be used to classify wheat genotypes into grain yield productivity classes. This study was conducted in north eastern Colorado near Greeley for two years, 2010 and 2011. The NDVI readings were taken weekly during the winter wheat growing season from March to late June in both years. The correlation between NDVI and grain yield was determined using Pearson's product-moment correlation coefficient (r). The coefficient of determination (R^2) was used to explain the proportion of variability between NDVI and grain yield. The K-means clustering was used to classify mean NDVI and mean grain yield into three classes. Our results indicate more consistent association between grain yield and NDVI later in the season, after anthesis and during mid-grain filling stage under dryland and poor association in wheat grown in irrigated conditions. Below saturation of NDVI values (about 0.9), (i.e. prior to full canopy closure and after the beginning of senescence or most of the season under dryland conditions) we observed that NDVI could be used to predict grain yield. Our results also indicate that NDVI readings successfully classified

wheat genotypes across dryland and irrigated conditions. This study demonstrates the potential of using NDVI readings as a tool to differentiate and identify superior wheat genotypes.

INTRODUCTION

Precision agricultural practices have significantly contributed to the improvement of crop productivity and profitability. It enhances farm input use efficiency and reduces environmental impacts (Koch and Khosla, 2003). Today, precision agricultural practices are providing farmers with valuable information, enabling them to make the right decisions with respect to management of crop inputs such as fertilizer, seed, pesticides, water, etc.

Remote sensing is a key component of precision agricultural practices. It is used to monitor the crop development, and to provide rapid and nondestructive estimates of plant biomass, leaf area index (LAI), nitrogen (N) content and grain yield (Aparicio et al., 2000; Cabrera-Bosquet et al., 2011). Remote sensing techniques can be divided into two broad categories: active and passive. Passive remote sensing utilizes ambient light as its source of energy. Satellite and airborne imagery use passive remote sensing. Several studies have reported that passive sensors are useful in obtaining information about crop canopies. However, airborne or satellite borne passive sensors have many limitations such as expense and lack of ability to collect data at night or on cloudy days. In addition, they require advanced computing skills to manipulate and interpret imagery data (Erdle et al., 2011; Govaerts and Verhulst, 2010; Inman et al., 2005; Shaver et al., 2010, 2011).

Active remote sensing devices have their own source of energy. They were developed to overcome the limitations of passive sensing devices and to minimize the effects of ambient light conditions on reflectance readings (Tubaña et al., 2011). Active remote sensors can measure the amount of light reflected from the crop canopy at any time, day or night. This is because these sensors can differentiate between external light sources such as sunlight, and light generated from its own energy, a unique feature of active sensors (Schepers, 2008). Moreover, they are relatively inexpensive and easy to use. They are also small enough to be handheld or mounted on a tractor (Cabrera-Bosquet et al., 2011; Inman et al., 2005; Shaver et al., 2011). Active remote sensing tools such as Greenseeker® (NTech Industries Inc., Ukiah, California, USA) can measure vegetation indexes such as the Normalized Difference Vegetative Index (NDVI) or simple ratio (SR) using light reflectance from crop canopies. The NDVI is determined by the intensity of red light (R) and near-infrared light (NIR) reflected from the crop canopy. It is calculated using the following equation:

$$NDVI= NIR - R / NIR + R, \qquad \text{Eq.1}$$

where R is the reflectance in the red light band (wavelengths 600 to 720 nm) and NIR is the reflectance in the near-infrared band (wavelengths 720-1300 nm).

Reflectance of light from individual leaves is influenced by the internal structure of the leaf. Campbell (2002) reported that reflectance in the red and blue (wavelengths 400 to 500 nm) portion of the electromagnetic spectrum depended mainly on chlorophyll contained in the palisade layer of the leaf. In addition, 70% to 90% of incident light in the visible spectrum is absorbed by chlorophyll and is used for photosynthesis, while the green band (wavelengths 500 to 600 nm) is mostly reflected. The vegetation reflectance intensity in the visible light (VIS; waveband 400 to 720 nm) is negatively correlated to leaf N content, while NIR reflectance is positively correlated to leaf N content and biomass (Shaver et al., 2010). Reflectance of NIR depends on the structure of the mesophyll cells in the leaf and the cavities between them (Campbell, 2002). Plant anatomical characteristics are influenced by many environmental factors such as soil moisture, soil salinity, nutrient status or leaf age, all of which can affect reflectance measurements (Ma et al., 2001). A strong linear relationship exists between leaf N concentration and leaf chlorophyll concentration (Evans, 1989; Lamb et al., 2002). Greater leaf area and green plant biomass translate into higher NDVI values (Shaver et al., 2010, 2011). Since N content of the plant is directly related to leaf area and green plant biomass, higher N content in plants also results into higher NDVI values (Shaver et al., 2011). Raun et al. (2001) demonstrated that a significant relationship (R^2 = 0.5, p-value < 0.0001) exists between NDVI and estimated grain yield in winter wheat (*Triticum aestivum* L.). Likewise, Inman et al. (2007) found a linear relationship (R^2 = 0.65) between NDVI and grain yield in maize (*Zea mays* L.). Several other studies revealed significant correlation between NDVI and grain yield from heading to grain filling in wheat (Ball and Konzak, 1993; Marti et al., 2007; Prasad et al., 2007; Reynolds et al., 2001; Royo et al., 2003). The most appropriate stage for estimating yield was reported to be at mid-grain filling stage (Marti et al., 2007; Royo et al., 2003). Aparicio et al. (2000) found correlation between NDVI and grain yield increasing as growth stage progressed from booting to maturity, but it was significant only at the maturity stage for durum wheat [*Triticum turgidum* L. subsp. *durum* (Desf.) Husn.] under irrigated conditions. They also observed a positive correlation between NDVI and grain yield at all wheat growth stages under dryland conditions.

Breeding methods often focus heavily on grain yield as a trait to identify, select, and breed new crop varieties. Likewise, crop biomass, as measured by destructive sampling, is another trait that is often used in breeding programs to identify total aboveground weight and total N in crop tissue. Regan et al. (1992) reported that destructive sampling is an efficient method to select superior genotypes of spring wheat for early vigor under dryland conditions.

However, destructive sampling method is practical only when small numbers of samples are involved (Elliott and Regan, 1993). Direct estimation of grain yield and biomass through destructive sampling is tedious, expensive, labor intensive and time consuming (Babar et al., 2006b; Inman et al., 2005). Experience has also demonstrated that sampling errors cause difficulty in detecting prominent differences among samples and destructive sampling reduces the plot area for estimating final biomass and grain yield.

Active remote sensing based on NDVI can be used to estimate biomass and N variability in crop canopies without destructive sampling and thus has the potential to provide a fast, inexpensive, and accurate estimate of plant biomass production and grain yield of the genotypes prior to harvest, which would be beneficial for crop breeders (Elliott and Regan, 1993; Inman et al., 2005; Royo et al., 2003). Also, NDVI can detect subtle differences in sparse canopies which makes it suitable for estimating crop growth at early stages and it is not linear with respect to LAI of > 3.0 (Aparicio et al., 2002; Serrano et al., 2000). The NDVI values range between 0.0 and 1.0. The NDVI values from bare soil reflectance normally ranges between 0.1 and 0.2. The NDVI saturation normally happens around 0.9 when the NDVI reading fail to discern differences in variable crop canopies. Reynolds et al. (2001) suggested the use of NDVI as a fast screening tool for grain yield. Similarly, Araus et al. (2001) showed that a spectral vegetation index such as NDVI is a promising tool to screen genotypes.

In recent studies, it was shown that NDVI and other spectral reflectance indices have the potential to differentiate spring wheat genotypes from heading to grain filling stages for crop biomass and grain yield under irrigated conditions (Babar et al., 2006a, 2006b). Ma et al. (2001) reported that NDVI could differentiate between high and low grain yield among soybean [*Glycine max* (L.) Merr.] genotypes. They concluded that NDVI can be a reliable and fast index for screening soybean genotypes and estimating yield under irrigated conditions. However, review of the literature indicates that very few studies have been conducted to identify and differentiate winter wheat genotypes for grain yield using active sensor based NDVI.

The overall goal of this study was to evaluate the possibility of using Greenseeker®, measuring red NDVI, as a tool to differentiate and classify wheat genotypes. The specific objectives were: (i) to determine if active sensor-based NDVI readings can differentiate among wheat genotypes, and (ii) to determine if NDVI readings can classify wheat genotypes into grain yield productivity classes.

MATERIALS AND METHODS

Study sites

This study was conducted in northeastern Colorado over two winter wheat growing seasons, 2009-2010 and 2010-2011 referred to as site years I and II respectively. The study was located at the USDA-ARS Limited Irrigation Research Farm, near Greeley, Colorado (40˚ 26′ 58.87″ N and -104˚ 38′22.56″ W). Both site years were under drip irrigation, and soils were mapped as Otera sandy loam (coarse–loamy, mixed superactive, calcareous, mesic Aridic Ustorthents) soil series with zero to three percent slope (Crabb, 1980). The soils were deep, well-drained and were formed by eolian deposits and mixed outwash parent material and included loam and clay loam underlying material. In site year I (2009-2010), the total precipitation received during the crop growing season from October 1, 2009 to July 31, 2010 was 292.9 mm. For site year II (2010-2011), the total precipitation received from October 1, 2010 to July 31, 2011 was 209.3 mm (USDA, 2012). The total precipitation received during the two site years was higher than the ten year average precipitation of 170.6 mm for the same time periods.

The previous crop was dry (pinto) beans (*Phaseolus vulgaris* L.) under dryland and irrigated conditions for both years.

Experimental Procedure

A global positioning system unit was used to map the field boundaries and to geo-reference soil samples (Trimble Ag 114 GPS antennae with differential correction, CA, USA). Soil samples were collected using a systematic unaligned grid sampling design for the entire study area in both site-years. Thirty soil samples were collected at two depths, 0 - 20 cm and 20-61 cm, at 15 locations within the 0.2 hectare study area (i.e. a sampling density of 72 samples per ha). Soil samples consisting of several soil cores were collected from each depth to obtain one composite soil sample. Soil samples were dried and sent to a commercial laboratory (Ag Source Harris Lab., Lincoln, NE) for chemical and physical soil property analysis. Particle size analysis was determined by using the hydrometer method (Gee and Bauder, 1986). Soil pH was measured using 1:1 water to soil slurry (Thomas, 1996). Organic matter (OM) was determined using the loss on ignition method (Heiri et al., 2001). Soil NO_3-N was measured using the cadmium reduction method (Mulvaney, 1996). A summary of soil properties for both sampling depths across the two site years is presented in Table 1.1.

Table 1.1 Summary of soil properties for soil samples acquired at depths of 0-20 cm and 20-61 cm. Soil NO_3-N contents were determined on samples collected on March 22nd (at early spring) and August 19th of 2010 (after harvest) for site year I and November 8th 2010 (at early fall) and August 22nd 2011(after harvest) for site year II.

Site year	Sampling depths (cm)		pH	O.M %	N at early spring $Mg\ g^{-1}$	N after harvest $Mg\ g^{-1}$	Sand %	Silt %	Clay %	Soil texture
I	0-20	Min	7.9	1.0	22.0	5.0	64.8	13.6	9.6	Sandy Loam
		Mean	8.0	1.1	31.0	7.9	68.4	16.5	15.1	
		Max	8.1	1.3	47.0	14.0	72.8	21.6	17.6	
	20-61	Min	7.9	0.9	11.0	5.0	60.8	13.6	11.6	Sandy Loam
		Mean	8.0	1.1	22.3	12.5	67.7	16.9	15.3	
		Max	8.2	1.3	40.0	37.0	72.8	21.6	17.6	
Site year	**Sampling depths (cm)**		**pH**	**O.M %**	**N at early fall $Mg\ g^{-1}$**	**N after harvest $Mg\ g^{-1}$**	**Sand %**	**Silt %**	**Clay %**	**Soil texture**
II	0-20	Min	7.8	1.0	30.0	8.0	58.8	4.4	12.8	Sandy Loam
		Mean	8.0	1.2	38.0	15.4	64.9	16.7	18.4	
		Max	8.1	1.5	54.0	22.0	70.8	24.4	30.8	
	20-61	Min	8.0	0.8	16.0	4.0	53.2	3.6	15.2	Sandy Loam
		Mean	8.2	1.0	22.4	9.8	61.7	17.7	20.5	
		Max	8.4	1.3	44.0	22.0	67.2	27.6	29.2	

This study was a part of a large ongoing multi-disciplinary project. The experimental design for the large multi-disciplinary project was a split plot design. The data used in the study was analyzed as randomized block design, where the blocks are the replications and the experimental units are the 24 wheat genotypes. Site years and irrigation methods (dryland and irrigated conditions) were analyzed separately. Water application in the irrigated conditions was done based on climatological estimates of crop water use and evaporative demand. Twenty-four winter wheat genotypes were planted under both irrigated and dryland conditions. The genotypes were: Above, Ankor, Arlin, Avalanche, Baca, Bill Brown, Bond CL, CO940610, Danby, Goodstreak, Hatcher, Jagalene, Jagger, Keota, NuDakota, Platte, Prairie Red, Prowers

99, Ripper, RonL, Sandy, Snowmass, TAM 112, and Yuma. Dimensions of individual experimental plots were 3.7 m x 1.4 m with 6 plant rows at spacing of 22.8 cm between each row. Site years I and II were planted on October 11th (2009) and October 8th (2010) respectively, at a rate of 197,600 seeds ha^{-1}. Nitrogen and phosphorus fertilizers were applied prior to planting on September 29th, 2009 and October 7th, 2010 under dryland and irrigated conditions for site year I and II respectively. Nitrogen dry fertilizer was applied at a rate of 84 and 112 kg N ha^{-1} as Urea (46-0-0) and phosphorous dry fertilizer was applied at a rate of 56 and 44.8 kg P_2O_5 ha^{-1} as Mono-Ammonium Phosphate (11-52-0) for site year I and II respectively. Also, liquid Ammonium Phosphate was applied at rate 46.8 liter ha^{-1} (10-34-0) with wheat seed as a starter.

Crop biomass samples were collected five times during the growing season at various crop growth stages referred to as: early spring, jointing, anthesis, mid-grain filling and maturity. The early spring stage corresponds to the Feekes growth stage of 3 to 4 (tillers formed-leaf-sheaths lengthen), and jointing stage corresponds to the Feekes growth stage 6 (first visible node of stem). The anthesis stage corresponds to the Feekes growth stage 10.5 (flowering); the mid-grain filling stage corresponds to the Feekes growth stage 11.1 (milky ripe), and the maturity stage corresponds to the Feekes growth stage 11.4 (ripe for cutting and dead straw) (Large, 1954). Crop biomass samples consisted of 0.5 m row length acquired from each plot. Harvest biomass samples were determined with a 1 m row length and were taken from the middle of the experimental plot. Biomass samples were pulled up, bagged, and transferred to a cooler and stored at 4 ^{o}C until processed. Plants were freed from their roots and were placed into an oven to dry at about 68 ^{o}C until they reached a constant weight. Approximately ten to fifty plants were used per plot and then total aboveground biomass samples weighted, grinded, and analyzed to identify total N in crop tissue. The variation in the number of plants per sample across plots was due to taking a fixed length of row (0.5 m for all biomass samplings except at maturity when a 1-m length of row was sampled) as opposed to a fixed number of plants. The plots were harvested by plot combine on June 28th under dryland and July 6th under irrigated for site year I. For site year II plots were harvested on June 28th under dryland and July 7th under irrigated to measure grain yield.

Active remote sensing

Active remote sensing based NDVI measurements were acquired using a Greenseeker® Model 505 handheld optical sensor (NTech Industries Inc., Ukiah, California, USA). The principles of operation of the Greenseeker® were illustrated in Inman et al. (2005). The Greenseeker® generates light at two wavelengths: visible red light (R) at 656 ± 25 nm, and near-infrared (NIR) at 774 ± 25 nm (NTech, 2009). The Greenseeker® sensor is referred to as a "red sensor" and it measures light reflected from the plant canopy to calculate the NDVI. The field-of-view of the sensor is about 61cm by 1.5 cm (NTech, 2009). In-field reflectance measurements were taken by holding the Greenseeker® unit about 90 cm above the crop canopy and walking in the center of each wheat plot. Each plot was sensed for approximately two to five seconds, collecting 20 to 50 NDVI readings. The reflectance measurements were acquired weekly between 10:00 am and 2:00 pm on cloud-free days. Readings were collected from early spring wheat growth stage (March 29th, 2010) to after the mid-grain filling stage (June 21st, 2010) for site year I, and from March 21st, 2011 to June 27th, 2011 for site year II (Fig.1.1).

Figure 1.1 The NDVI readings were collecting using Greenseeker® handheld optical sensor. Plot boundaries are highlighted with white dashed lines.

Statistical analysis:

Statistical analysis was performed to determine differences among grain yield and NDVI readings for twenty-four wheat genotypes using analysis of variance (ANOVA) in statistical software R (R Development Core Team, 2010). Preliminary analysis indicated a significant interaction between the genotypes and plot replication indicating significant site differences across replications. This complicates the interpretation of the results since the response of NDVI to genotype cannot be explained just in terms of the main effects, (i.e.) wheat genotype. Hence, a three-step process was used to remove the site effect from the data prior to detailed statistical analysis. The first step was to remove the effect of genotype from the NDVI readings. This was accomplished by a regression analysis on NDVI data against genotypes using a general linear model (GLM). The residuals from the GLM represent the site effect. The next step was to model the spatial structure of the residuals using a semi-variogram. The semi-variogram model was fit to several theoretical variogram models (e.g., Gaussian, exponential and spherical) using the method of least squares. The model that minimized the Akaike information criterion (AIC) was selected to estimate the site effect for each observation in the data using simple kriging. The final step was to subtract the estimated site effect from the observed raw data. This adjusted data set was then analyzed using ANOVA to test for the significance of genotype and replication effects. When no significant interaction between genotype and replication was observed, the approach was deemed to be successful. Pairwise comparisons were made among genotypes using Tukey HSD test.

For the purpose of illustrating spatial variability in the dataset, inverse distance weighting was used to interpolate the raw NDVI values for each treatment and date by using ArcGIS Version 9.3 (ESRI Inc., Redlands, CA.).

The linear relationship between NDVI and grain yield was determined by using Pearson's product-moment correlation coefficient (r) measuring strength of association between NDVI and grain yield. In addition, linear regression between NDVI and grain yield was performed using the following model:

$$y = mx + b, \qquad \text{Eq 2.}$$

where y is the grain yield, m is the slope of the line, x is the NDVI and b is the intercept of the line. The coefficient of determination (R^2) was used to explain the proportion of variability in grain yield explained by variability in NDVI.

In order to create yield productivity classes, three clustering methods were used to classify grain yield: (i) K-means clustering algorithm: (ii) subjective clustering; and (iii) stratification clustering. The mean grain yield was classified into three classes (e.g. low, medium and high) for each clustering method. The NDVI data were also classified to create three classes (e.g. low, medium and high). For NDVI data, two methods were used: K-means clustering algorithm, and stratification clustering. The NDVI classes were generated independently for each of the 11 or 14 dates for site year I or site year II respectively and likewise independently for both dryland and irrigated conditions. The K-means clustering method aims at dividing data into classes or clusters that minimize the within cluster sum of squares (described in detail by Hartigan and Wong, 1979). Stratification clustering was based on the "cumulative square root of the frequency" method described in detail by Scheaffer et al. (1990). The subjective clustering method approach was based on knowledge of researchers or cooperating producers to rank wheat genotypes as high, medium or low yield potential (Khosla et al., 2008, 2010). As opposed to genotype yield potential, no prior information was available to subjectively classify the genotypes by their expected NDVI values. Therefore, yield was classified using three methods (e.g. k-mean, stratification and subjective) while NDVI was classified using only two methods (e.g. k-mean and stratification). The NDVI or grain yield averaged across the three replications was used to classify the 24 wheat genotypes into three classes. In order to verify the performance of the clustering methods, the three clustering grain yield methods and the two NDVI clustering methods were used to build contingency tables (Hornung et al., 2006) using each possible combination of methods (e.g. k-means on yield vs. stratification on NDVI). The overall accuracy of agreement between grain yield and NDVI for 24 wheat genotypes was used to determine which of the six different combinations of methods would perform the best. The best combination of methods would then be used to measure the overall accuracy of NDVI classes against yield classes, which is the main objective of this chapter.

RESULTS AND DISCUSSION

NDVI variations across *growth stages*

Statistical analysis using ANOVA revealed significant differences among the twenty four wheat genotypes ($p < 0.05$) based on NDVI readings. Differences were observed for all 11 dates in 2010 and all 14 dates in 2011 under both irrigated and dryland conditions. As expected, the NDVI values were low in early spring for both site years on March 29th and March 21st. At this growth stage early jointing, the mean NDVI value was 0.20 under both dryland (Fig.1.2) and under irrigated conditions (appendix A. Fig A.1) for site year I. For site year II the mean NDVI values were 0.23 and 0.21 under dryland and irrigated conditions, respectively (appendix A. Fig A.2 and 3). The NDVI values gradually increased with crop growth and reached a plateau in mid-season, between jointing and anthesis growth stages. The maximum NDVI values in mid-season were around 0.89 (mean value was 0.83) under dryland (Fig. 1.2) and 0.91 (mean value was 0.89) under irrigated conditions (appendix A. Fig A.1) for site year I. For site year II the maximum NDVI values in mid-season were 0.66 (mean value 0.48) under dryland and 0.85 (mean value 0.83) under irrigated conditions (appendix A. Fig A.2 and 3). The low NDVI values during mid-season in site year II is reflective of the drought conditions the crop was experiencing. As expected, the NDVI values decreased at the end of the season (in June, anthesis to mid-grain filling stages). The mean NDVI values in late season were 0.34 under dryland (Fig.1.2) and 0.58 under irrigated conditions (appendix A. Fig A.1) for site year I. For site year II the mean NDVI values were 0.24 under dryland and 0.62 under irrigated conditions (appendix A. Fig A.2 and 3). Again, lower NDVI values under dryland conditions than in the irrigated conditions at the end of season is reflective of water stress that crop experienced in water limited environment and was translated into NDVI values. Times-series of maximum, minimum and mean NDVI values for site year I in dryland plots are presented in Fig.1.2. Time series graphs for irrigated plots for site year I and for site year II in both dryland and irrigated plots (appendix A) had trends similar to that reported in Fig.1.2.

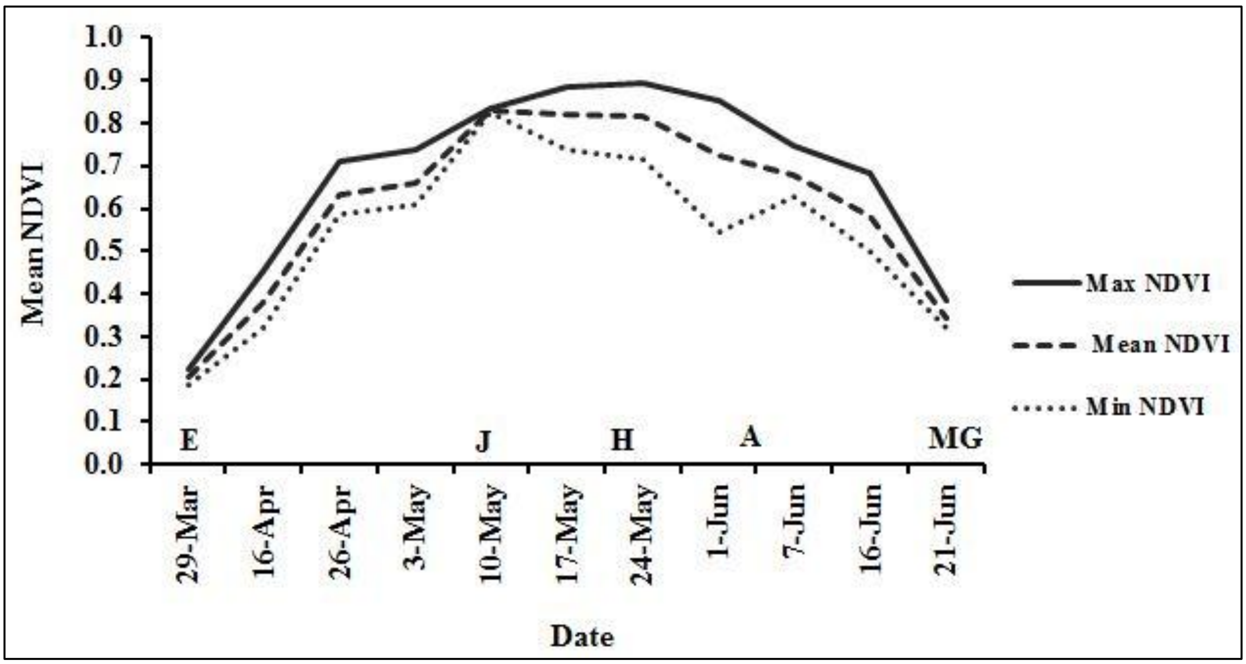

Figure 1.2 Time-series of maximum, minimum and mean NDVI values for individual winter wheat genotype (CO940610) selected across the growing season under dryland conditions for site I (11 dates for NDVI readings). Crop growth stages are indicated as E=early spring, J= jointing, H= heading, A= anthesis, and MG= mid-grain filling.

Our results indicate that NDVI values accurately characterized the generalized wheat crop growth curve. The NDVI values consistently increased with crop growth stages in early season and it reached a plateau when the ground surface was completely covered by the canopy. The plateau in NDVI values seems to correspond to the saturation of the sensor that loses sensitivity to changes in vegetation amount when LAI is higher than 3 (Aparicio et al., 2000;

Carlson and Ripley, 1997; Duchemin et al., 2006). The NDVI decrease at the end of the season is attributed to physiological maturity, change in crop color and senescence leaf, which increases red band reflectance and decreases NIR band reflectance. This phenomenon was observed by Aparicio et al. (2000) and Prasad et al. (2007) on vegetation with lower amount of green biomass due to either water stress or to normal senescence through the mid-grain filling stage. As expected, we observed increasing green biomass from early spring to mid-season and decreasing green biomass from mid-season to late season, which was reflected into NDVI values. Other reflectance based indices such as green NDVI (GNDVI) and SR can also detect seasonal variations in green biomass (Babar et al., 2006a; Prasad et al., 2007).

In-field spatial variability of winter wheat

In-field spatial variability in NDVI across wheat genotypes was observed in both site years and under both dryland and irrigated conditions (appendix A. Fig. A.4, 5 and 6). Visual assessment of NDVI maps indicates that a higher level of spatial variability existed under dryland conditions for site year II (Fig1.3) across 24 wheat genotypes. This may potentially be explained by different water stress responses across genotypes, which could differently affect the chlorophyll content and green biomass from one genotype to the other (Aparicio et al., 2000). Spatial variability of NDVI measurements was also observed by Verhulst and Govaerts (2010) and by Verhulst et al. (2009).

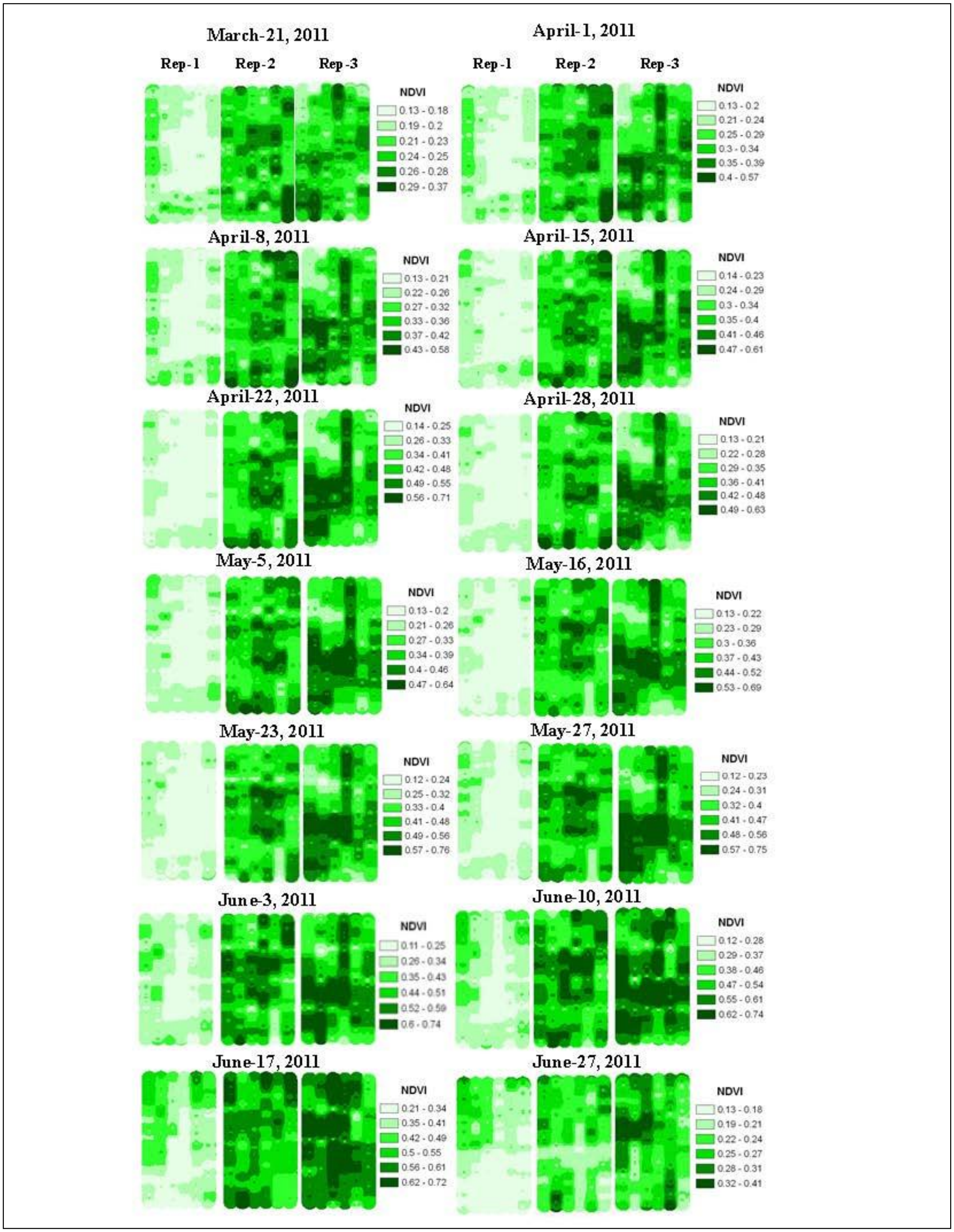

Figure 1.3 Maps of spatial variability in NDVI values across 24 winter wheat genotypes collected under dryland conditions for 14 dates across site year II.

Grain yield of genotypes

There was no significant difference (p-value < 0.05; Appendix A) in grain yield among the 24 winter wheat genotypes in site year I under either dryland or irrigated conditions. In site year II, there was a significant difference (p-value < 0.05) in grain yield among the 24 winter wheat genotypes under both dryland and irrigated conditions. The grain yield ranged from 1.57 to 6.43 (mean value 3.98) Mg ha^{-1} under dryland conditions and from 5.34 to 9.49 (mean value 7.11) Mg ha^{-1} under irrigated conditions for site year I. For site year II, grain yield ranged from 1.41 to 5.54 (mean value 3.51) Mg ha^{-1} under dryland conditions and from 5.27 to 10.93 (mean value 7.94) Mg ha^{-1} under irrigated conditions. Under dryland conditions, site year I had significantly (p-value <0.05) higher grain yield (mean yield 3.98 Mg ha^{-1}) than site year II (mean yield 3.51 Mg ha^{-1}) likely due to the amount of precipitation received for site year I. The site year I received approximately 84 mm additional growing season precipitation than that for site year II. On the other hand, site year II had significantly (p-value <0.05) higher grain yield (mean yield 7.94 Mg $ha^{-1)}$ than site year I (7.11 Mg ha^{-1}) under irrigated conditions. The variability in grain yield across the 24 wheat genotypes was high across both site years and under both dryland and irrigated conditions as illustrated by a difference between highest and lowest grain yield. Despite a large range of yield values across genotypes under both conditions, the yield was not significantly different across genotypes in site year I due to a large sum of squares of the residuals as compared to the genotype and replication effect. Conversely, in site year II, the genotype and the replication effect were explaining most of the yield. Genotypic variability for grain yield and NDVI at different stages and between dryland and irrigated conditions was observed for both site years possibly due to different water status between the two conditions. Genotypic variability for yield was observed among 25 durum wheat genotypes within and across dryland and irrigated conditions, with winter wheat and with durum wheat under dryland conditions (Prasad et al., 2007; Royo et al., 2003).

Relationship between NDVI and grain yield

The correlation coefficient (r) between NDVI and grain yield with 72 observations (24 wheat genotypes times 3 replications) was significant for all growth stages (α=0.05). The highest correlation (r = 0.79) was observed at early season stage (March 29th) as well as late in the growing season, at mid-grain filling stage (June 21st) under dryland conditions for site year I (Fig.1.4). Under irrigated conditions, the correlation coefficient between NDVI and grain yield was significant at early spring and anthesis (p-value > 0.05), and not significant at jointing and mid-grain filling stages (p-value < 0.05) for site year I (Fig.1.4). The highest correlation coefficient was observed in early spring stage on March 29th (r=0.47). For site year II, the correlation coefficient between NDVI and grain yield was significant (p-value < 0.05) for all growth stages, increasing from early spring to mid-grain filling stages. The highest correlation coefficient (r=0.91) was observed between anthesis and mid-grain filling stages (Fig.1.4). Under irrigated conditions the correlation coefficient between NDVI and grain yield was significant for all growth stages (p-value < 0.05). The highest correlation coefficients were observed at early spring (r=0.53) and after mid-grain filling (r=0.54) stages. A weak correlation was observed at anthesis stage for site year II as illustrated in Fig.1.4.

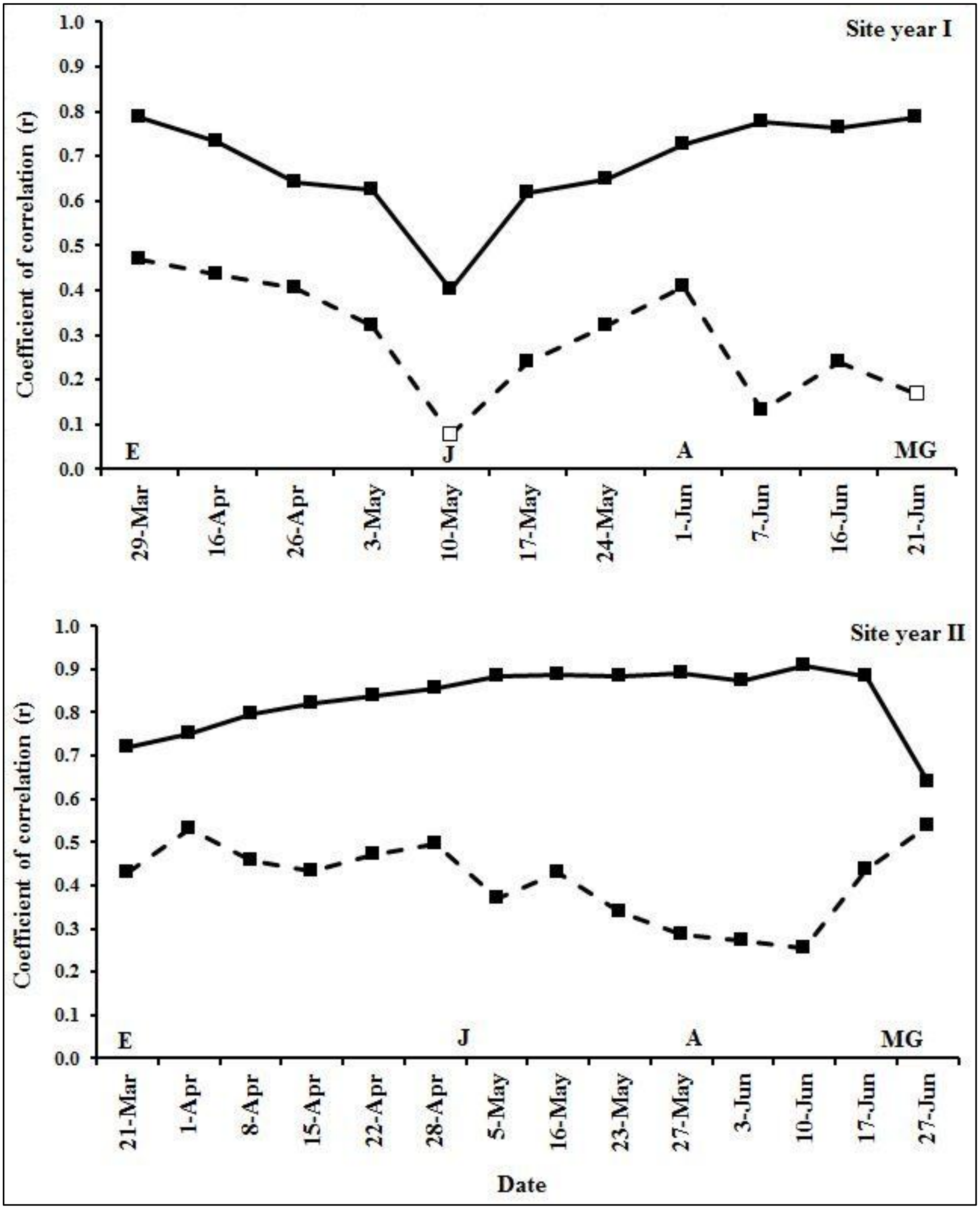

Figure 1.4 Correlation coefficient (r) between NDVI and grain yield across 24 winter wheat genotypes for site year I and II under dryland (solid line) and irrigated (dashed line) conditions across crop growth stages. E=early spring, J= jointing, A= anthesis, and MG= mid-grain filling. Solid symbols indicate significant correlation between NDVI and yield (p-value <0.05).

The correlation coefficient (r) between NDVI and grain yield was the lowest at jointing under dryland conditions for site year I. This could potentially be attributed to normal growth in crop biomass at this growth stage and to the amount of precipitation received (approximately 84 mm more precipitation than for site year II during growing season). Low r square in the mid-season under dryland conditions in site year I was potentially related to a large precipitation event (61.21 mm of rain over eight days at this growth stage) could have led to higher biomass, chlorophyll content and canopy cover which may have resulted in NDVI saturation. This was also observed under irrigated conditions for both site years. Nevertheless, our results suggest thatNDVI could assist in assessing grain yield at early spring and after anthesis to mid-grain filling growth stages under dryland conditions when the NDVI values are below the saturation level of 0.9. Findings of this study are consitent with previous studies. A positive correlation was observed between NDVI and grain yield with durum wheat stages under dryland conditions (Aparicio et al., 2000). Also, a positive correlation between NDVI and grain yield was observed at anthesis and mid-grain filling stage (Marti et al., 2007; Royo et al., 2003).

Figures 1.5 and 1.6 illustrates the relationship between NDVI and yield as assessed by regression analysis. The coefficient of determination (R^2) shows the strength of the relationship between NDVI and grain yield for all stages under dryland conditions. The relationship was the weakest at jointing stage (R^2=0.16), and the strongest (R^2=0.62) at early season and mid-grain filling (Fig. 1.5). The weakest relationship (R^2=0.41) was observed after mid-grain filling and the strongest relationship (R^2 =0.83) just before mid-grain filling (Fig. 1.5). Under irrigated conditions, the coefficient of determination (R^2) was low, indicating a weak relationship between NDVI and grain yield for all growth stages in both site years. The strongest relationship was observed at early spring in both site years (Fig. 1.6).

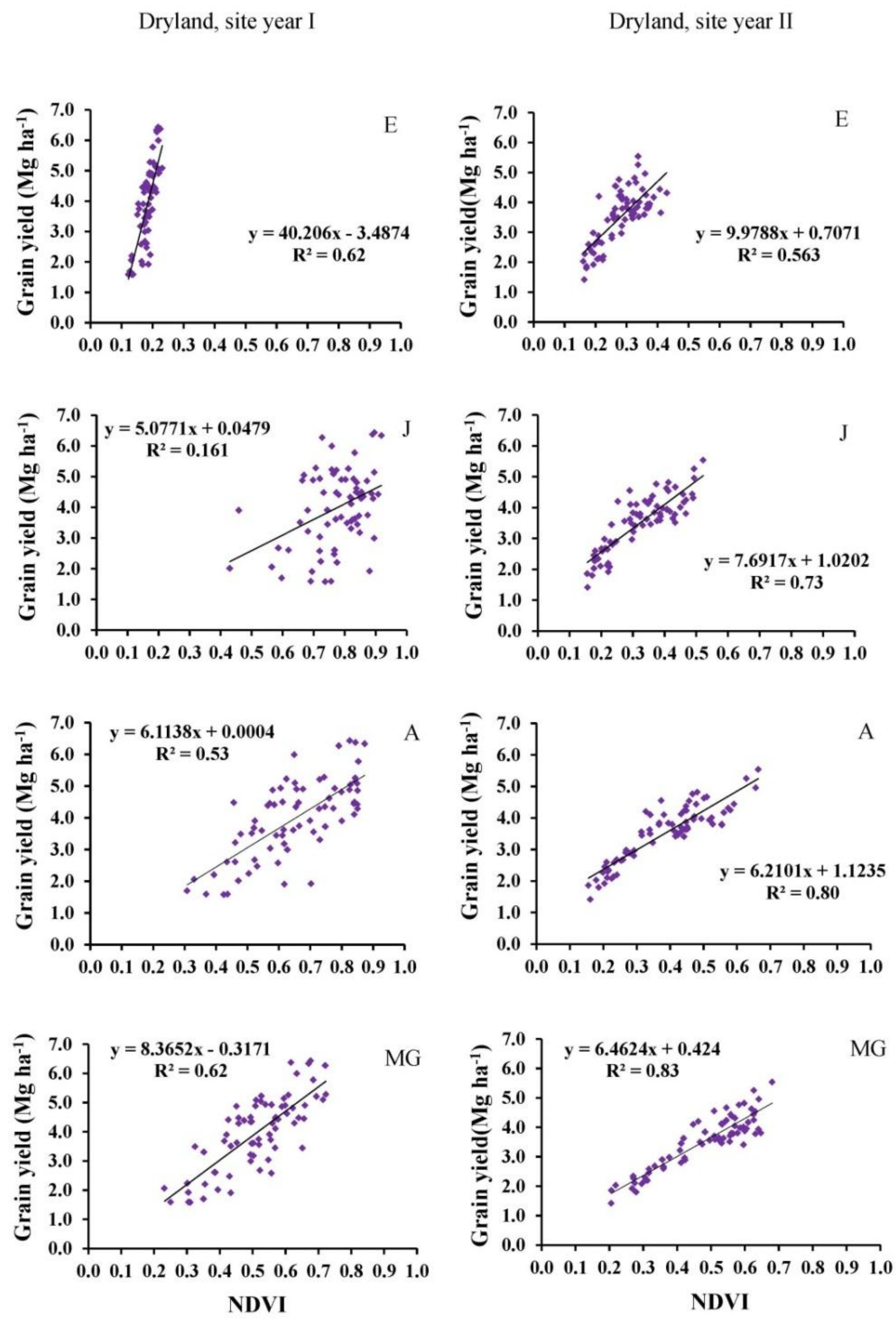

Figure 1.5 Relationship between NDVI and grain yield across 24 winter wheat genotypes under dryland conditions across crop growth stages. Crop growth stages are indicated as E=early spring, J= jointing, A= anthesis, and to MG= mid-grain filling.

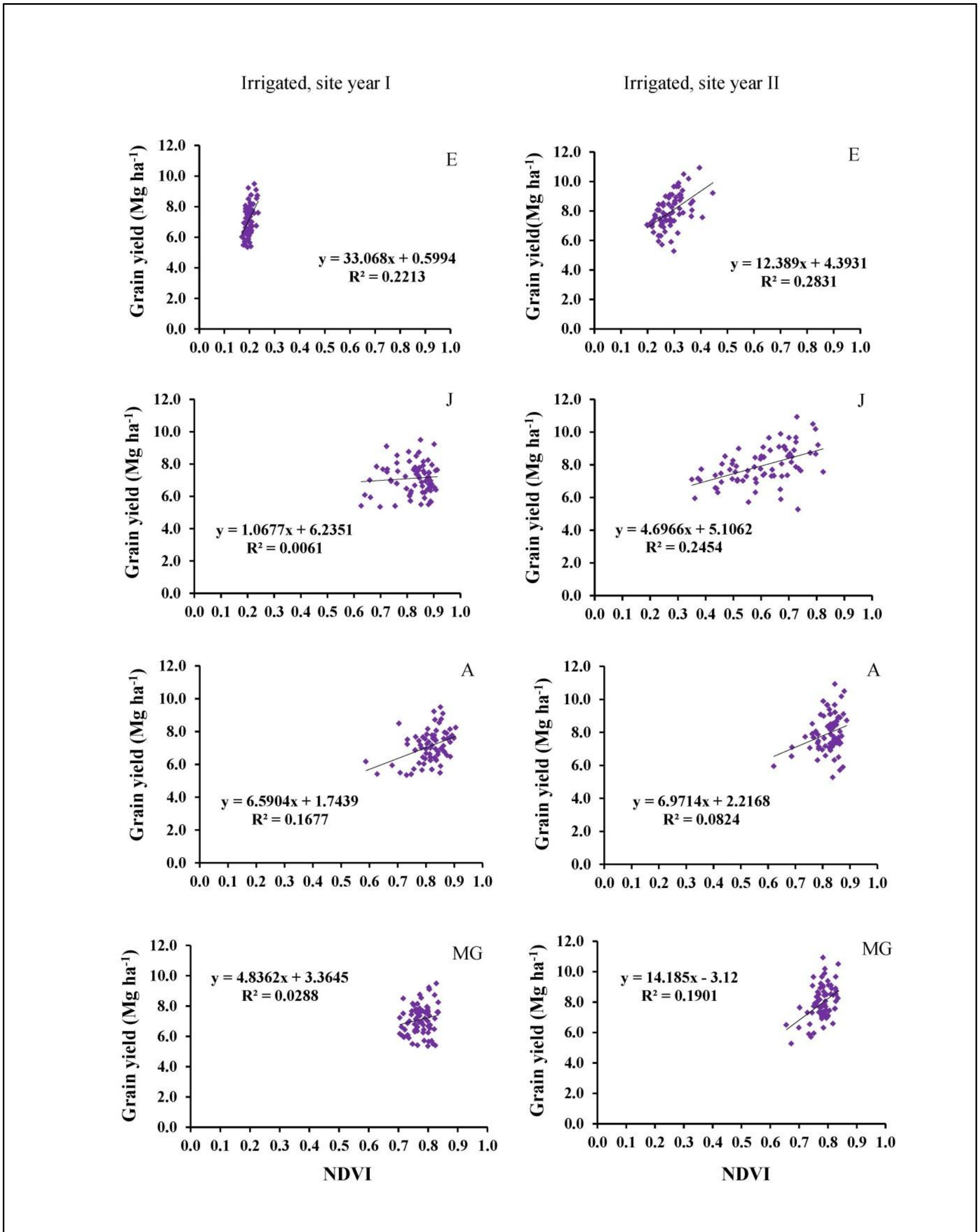

Figure 1.6 Relationship between NDVI and grain yield across 24 winter wheat genotypes under irrigated conditions across crop growth stages. Crop growth stages are indicated as E=early spring, J= jointing, A= anthesis, and to MG= mid-grain filling.

Comparing NDVI and yield classification

The two clustering methods (K-means and stratification clustering) employed in grain yield data classification produced almost the same results under both dryland (Fig. 1.7a) and irrigated conditions (Fig. 1.7b). Based on contingency table analysis, the overall accuracy between NDVI classes (either K-means or stratification clustering) and subjective classification of yield potential was low. For this reason and since the K-means clustering method is widely used by the scientific community, the K-means clustering method results were selected to show agreement of classification between grain yield classes and NDVI classes (Figs. 1.8 and 1.9).

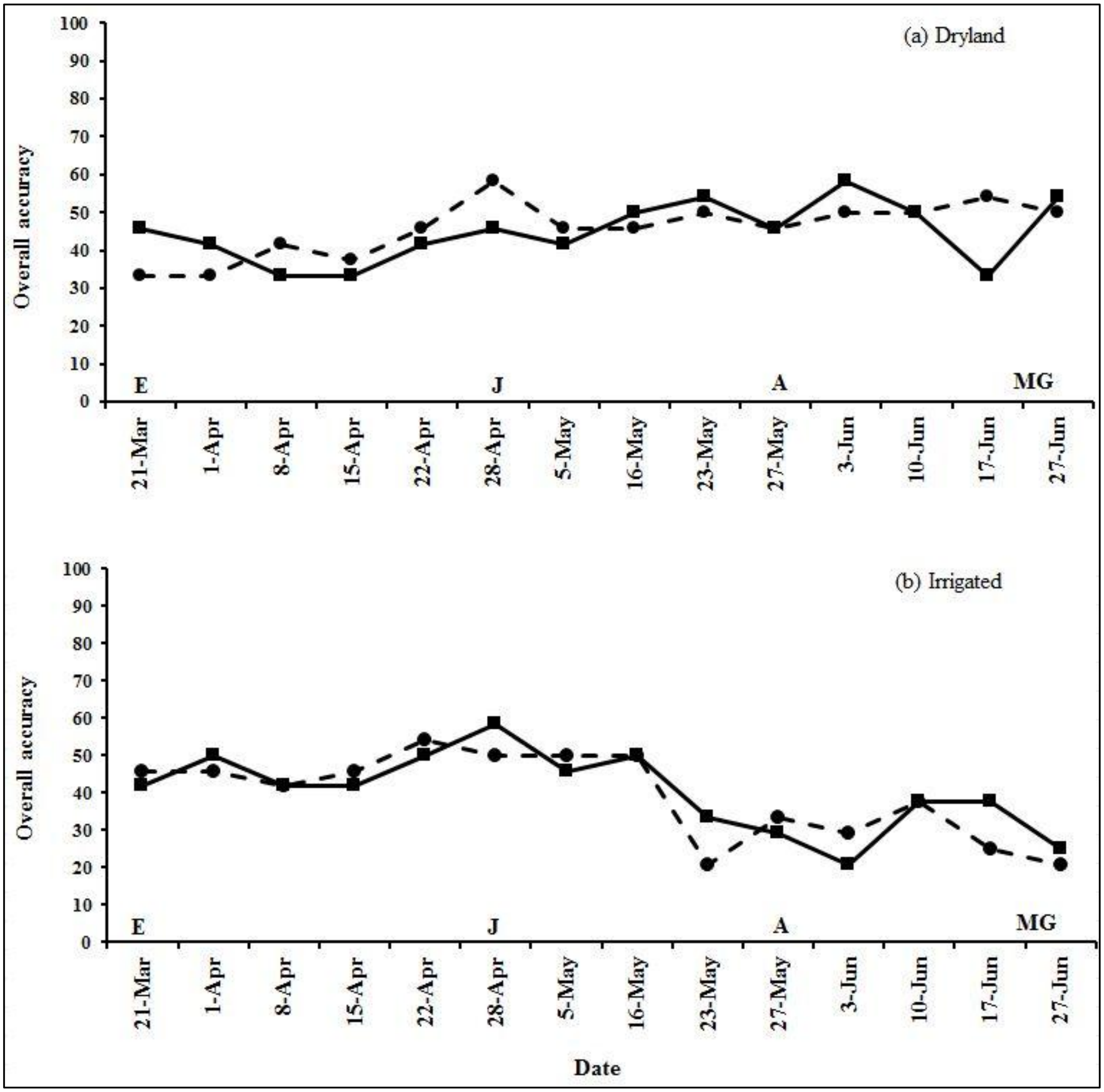

Figure 1.7 Overall accuracy results from contingency table comparing mean grain yield classes to mean NDVI classes using K-means clustering (solid line with squares) and stratification clustering (dashed line with circles). The overall accuracy is presented across 14 dates for site year II under (a) dryland conditions and (b) irrigated conditions. E=early spring, J= jointing, A= anthesis, and MG= mid-grain filling.

K-means clustering method

The quantitative clustering approach consisted of using K-means clustering algorithm (three clusters) to classify the 24 wheat genotypes based on the average NDVI values and based on the average grain yield across the three replications for each date. Table 1.2 presents a contingency table that compares grain yield classes to NDVI classes for all dates and both site years in this study.

Table 1.2 Contingency table comparing grain yield classes to NDVI classes for all dates, site years and water regimes (dryland and irrigated conditions) in this study merged together. The overall accuracy is presented in the lower right end of the table.

	---------NDVI class--------			
Yield class	Low	Medium	High	% accuracy
Low	203	168	100	43.1
Medium	137	204	139	42.5
High	28	94	127	51.0
% accuracy	55.2	43.8	34.7	44.5*

*Overall accuracy = Sum of diagonal values x 100 / Sum of the whole table

The diagonal sum of the contingency table gives the overall accuracy of the agreement between grain yield and NDVI classes. The overall accuracy measured over the whole dataset of this study was 44.5 %. For site year I, the overall accuracy between NDVI (all 11 dates together) and grain yield was 50.8% and 43.2% under dryland and irrigated conditions respectively. For site year II, the overall accuracy between NDVI (all 14 dates together) and grain yield was 44.9% and 40.2% under dryland and irrigated conditions respectively. The results show that overall accuracy under dryland conditions was higher than overall accuracy under irrigated conditions for both site years. As per overall accuracy results for dryland conditions, clustering the genotypes as low, medium or high classes did not improve the correlation between yield and NDVI (Fig.1.8 and 1.9). As compared to a correlation coefficient observed between NDVI and grain yield with 72 observations (Figs. 1.4) across two site years. In site year I, under irrigated conditions, the clustering of genotypes into three classes improved the overall accuracy (Fig. 1.8) in general as compared to correlation coefficient over 72 observations (Fig. 1.4). For site year II, there was improvement in correlation only in mid-season using clustering of genotypes (Fig. 1.9) as compared to a correlation coefficient between NDVI and grain yield with 72 observations (Fig. 1.4). We thus believe that clustering the genotypes into classes rather than comparing them independently could be useful when there is canopy closure or high LAI. Indeed, in these circumstances, the sensitivity of NDVI diminishes due to saturation and only substantial variations in yield can be detected using the Grennseeker®.

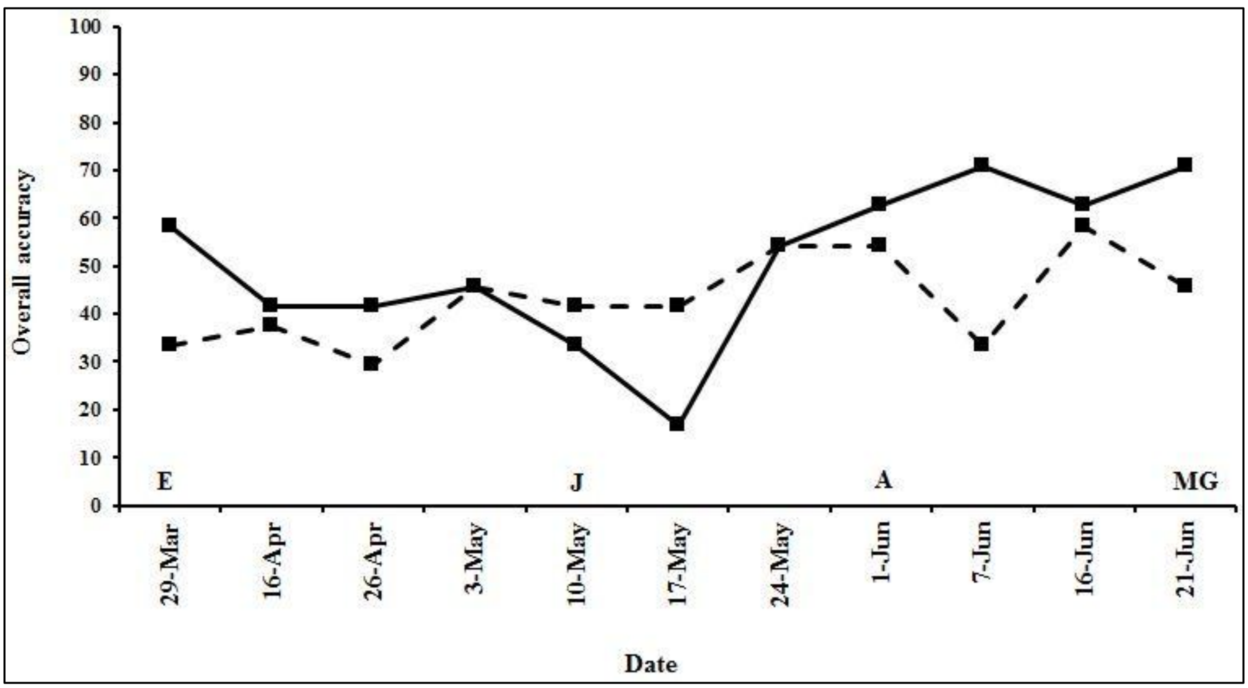

Figure 1.8 Overall accuracy between grain yield and NDVI classes for site year I (dryland with solid line and irrigated with dashed line). E=early spring, J=jointing, A=anthesis, MG=mid-grain filling stage.

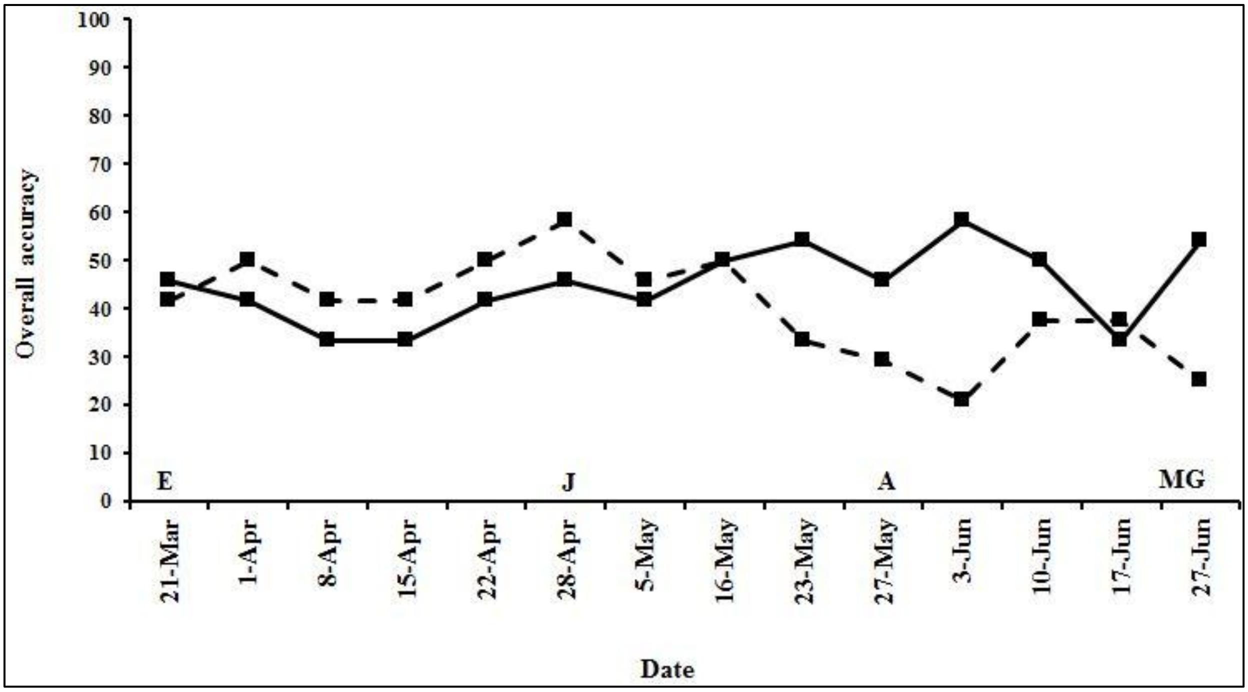

Figure 1.9 Overall accuracy between grain yield and NDVI classes for site year II (dryland with solid line and irrigated with dashed line). E=early spring, J= jointing, A= anthesis, and MG= mid-grain filling.

For dryland experiment, based on overall accuracy results comparing grain yield classes to NDVI classes, anthesis to mid-grain filling stages would be the most appropriate stages to classify wheat genotypes. As opposed to dryland conditions, the wheat genotypes grown under irrigated conditions did not respond similarly years. In site year I, the overall accuracy was higher later in the season while in site year II, the overall accuracy was higher early in the season. In general, the decrease in the correlation and overall accuracy results between NDVI and grain yield across 24 wheat genotypes coincided with mid-season, when NDVI saturated. The NDVI index normally reaches a plateau with a LAI of three or more (Aparicio et al., 2002; Carlson and Ripley, 1997). When NDVI plateaus (or saturates), it loses its sensitivity to variations in biomass, LAI or chlorophyll content. It was reported that, with a LAI above 3, canopy closure is reached, and red reflectance decreases to minimum values (around 3 to 4 % of incident light) because 70 to 90 % of incident light is absorbed by chlorophyll in the upper leaves and the rest is transmitted (Aparicio et al., 2002). In contrast, the NIR reflectance increases with canopy closure because chlorophyll reflects NIR more than bare soil (Aparicio et al., 2002). Therefore, NDVI saturates because of low red reflection in crop canopy and not because of Greenseeker® sensitivity.

Our results partially support our hypothesis according to which it is possible to use active sensor based NDVI as a tool to differentiate and classify wheat genotypes. In general the results showed that NDVI differentiates and classifies better after anthesis and in mid-grain filling stages. Also, classification is better under dryland than irrigated conditions. The potential of spectral reflectance indices to differentiate for grain yield was also observed on wheat genotypes under irrigated conditions (Babar et al., 2006a). However, Babar et al. (2006a) did not use Greenseeker® sensor to obtain reflectance, but rather a portable narrow-bandwidth spectroradiometer (Model Field-Spec UV/VNIR, Analytical Spectral Devices, Boulder, CO). Our results indicate that breeders who work on drought resistant traits and grow wheat in dryland may benefit from uses NDVI as a screening tool more than breeders who grow wheat in irrigated condition for other traits such as disease resistance or nitrogen use efficiency for example. The potential of NDVI for screening and ranking genotypes based on their grain yield was also demonstrated on soybean genotypes (Ma et al., 2001). We thus believe that the use of NDVI as a tool to identify high yielding genotypes also has potential with crops other than wheat.

It is important to mention that the Greenseeker®'s active sensor was developed to detect N stressed plants for variable rate nitrogen management and not necessarily to differentiate healthy genotypes. Therefore, more research could be done to identify wavebands that would be specifically efficient at differentiating genotypes that are not N-stressed and for which reflectance would not tend towards zero in healthy canopy readings, as it is the case for red reflectance. This could allow differentiation of genotypes at any growth stage and water management conditions.

CONCLUSION

Active remote sensing based on NDVI was assessed as a tool to identify and differentiate wheat genotypes. A strong relationship was observed between NDVI and grain yield across 24 wheat genotypes under dryland conditions. Our results suggest that NDVI could assess grain yield under dryland conditions but show limitations under irrigated conditions. The overall accuracy between NDVI and grain yield classes across growth stages indicated that the most appropriate stage to identify and classify wheat genotypes was from anthesis to mid-grain filling stages. Our results also indicate that NDVI readings collected by Greenseeker® successfully classified wheat genotypes across dryland and irrigated cropping systems into grain yield classes. This study demonstrates the potential and limitations of using NDVI readings as a tool to differentiate and identify wheat genotypes based on their productivity potential. More work could be done to identify the best wavebands and indexes to specifically differentiate genotypes.

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CHAPTER II

Characterizing Variation in Nitrogen Use Efficiency for Wheat Genotypes across Dryland and Irrigated Conditions

SUMMARY OF CHAPTER II

Global nitrogen use efficiency (NUE) is estimated to be about 33% for cereal production. Increase in N fertilizer prices and growing environmental concerns are both reinforcing producers to improve NUE. The two main approaches to improve NUE are selecting genotypes for high NUE and improving nitrogen management. Remote sensing tools are helping improve NUE through nitrogen management and could also be useful in identifying high NUE genotypes. The objectives of this study were (i) to identify and quantify the main sources of variation in NUE across winter wheat genotypes (*Triticum aestivum* L.) and (ii) to determine if normalized difference vegetation index (NDVI) could characterize variability in NUE across wheat genotypes. This study was conducted on twenty-four winter wheat genotypes in north eastern Colorado in 2010 and 2011. The NDVI was measured weekly by Greenseeker®, and NUE was calculated as partial factor productivity and as partial nitrogen balance at the end of the crop growing season. The parameters (N uptake efficiency, N utilization efficiency, biomass production efficiency, and ratio of grain N content to biomass weight) related to NUE were also calculated to measure their relative importance in the variations of NUE. Our results indicate that nitrogen uptake efficiency was the main source of variation of NUE among genotypes. We observed a strong relationship between NDVI and NUE across the 24 wheat genotypes under dryland conditions and a poor association under irrigated conditions. These limitations seem to be linked to NDVI saturation. The results of this study indicate that NDVI is a good vegetative

index for prediction of NUE in sparse canopy but not necessarily in dense canopy with NDVI measured by Greenseeker®. This study demonstrates the potential and limitations of NDVI, collected by using Greenseeker®, to successfully characterize variability in NUE across wheat genotypes.

INTRODUCTION

Nitrogen (N) is an essential element for winter wheat (*Triticum aestivum* L.) growth and development (Lofton et al., 2010; Wang et al., 2011). Nitrogen fertilizer is used in wheat production to increase grain yield and quality (Giambalvo et al., 2010). Global N fertilizer consumption has increased in recent years to meet growing human needs (Snyder, 2009). However, only about 33% of N fertilizer applied translates into grain in cereal production (Raun and Johnson, 1999). The remaining N applied (about 67%) represents a $15.9 billion annual loss to cereal growers through leaching, gaseous release from plants, surface runoff, volatilization, and denitrification. It is believed that the N fertilizer applied to the soil that is not taken-up by plants contributes to environmental problems such as pollution of groundwater and greenhouse gas emissions. It is estimated that a mere 1% increase in crop nitrogen use efficiency (NUE) at a global scale would result into savings of about $ 234 million (Raun and Johnson, 1999). Improving NUE through genotype selection and/or crop management while increasing crop production and reducing environmental impact is challenging.

Nitrogen use efficiency is a term that indicates the relationship between the amounts of N fertilizer utilized by the crop against the amount of N fertilizer lost from the soil by various pathways as mentioned above. The NUE is affected by the ability of plants to uptake N from the soil and to convert absorbed N into grain (Baligar et al., 2001; Nelson et al., 2012). Review of current literature indicates more than 18 different definitions and methods of measuring NUE in cereal crops, four of which are most commonly used to calculate NUE (Table 2.1) (Hawkesford, 2012; Snyder and Bruulsema, 2007). Among the common definitions, NUE is defined as the grain yield produced per unit of N fertilizer applied, which is also referred to as partial factor productivity (PFP) (Nielsen, 2006; Snyder and Bruulsema, 2007). Likewise, NUE is also defined as the grain nitrogen content divided by nitrogen fertilizer applied and is also referred to as partial nitrogen balance (PNB) (Hawkesford, 2012; Snyder and Bruulsema, 2007). In addition, the Nitrogen Uptake Efficiency (UPE) and Nitrogen Utilization Efficiency (UTE) are considered as the most important components of NUE (Moll et al., 1982).

Table 2.1 Four common definitions and methods of calculating Nitrogen Use Efficiency (NUE) according to (Hawkesford, 2012; Snyder and Bruulsema, 2007).

NUE term	Calculation	Common values for cereal crops
PFP_N Partial Factor productivity of N applied	$PFP_N = GW/NS$	40-80 kg grain kg^{-1} N
AE_N Agronomic efficiency of applied N	$AE_N = (GW-GW_0)/NS$	10-30 kg grain kg^{-1} N
PNB_N Partial N balance (removal to use ratio)	$PNB_N = GN/NS$	0 to greater than 1 depends on native soil fertility and fertility maintenance objectives <1 in nutrient deficient systems (fertility improvement) >1 in nutrient surplus systems (under replacement) Slightly less than 1to 1 (system sustainability)
RE_N Apparent crop N recovery efficiency	$RE_N = (TN-TN_0)/NS$	0.3-0.5–N recovery in cereals-typical 0.5-0.8–N recovery in cereals-best management

GW – grain yield weight with N fertilizer supplied (kg ha^{-1})
NS – amount of N fertilizer supplied (kg ha^{-1})
GW_0 – grain yield weight (kg ha^{-1}) with no N fertilizer supplied
GN – grain N content with N fertilizer supplied (kg ha^{-1})
TN – total N in aboveground biomass at maturity (kg ha^{-1}) with supplied N
TN_0 – total N in aboveground biomass at maturity (kg ha^{-1}) with no supplied N

As presented in Table 2.1, there is a range of NUE values reported in the literature. The NUE values may vary because of a number of factors; however, genetics and environment are the major ones. Genetic variation in NUE was found across maize (*Zea mays* L.) and winter wheat genotypes (Barraclough et al., 2010; Moll et al., 1982; Van Sanford and MacKown, 1986). Several studies have mentioned UPE as a high contributing factor to variation observed in NUE under non-limiting N level studies in wheat (Dhugga and Waines, 1989; Van Sanford and

MacKown, 1986; Wang et al., 2011). Accordingly, Moll et al. (1982) found UPE as the main contributor to variations in NUE across maize genotypes at high N levels versus UTE being the main contributor to variations in NUE across maize genotypes at low N levels. In contrast, other authors (Giambalvo et al., 2010; Ortiz-Monasterio et al., 1997) reported that differences in NUE among durum wheat genotypes are mostly associated with differences in UTE at non-limiting N level. The disagreement among studies on UPE or UTE being the main contributor to variation in NUE are most likely related to differences in groups of genotypes, soil properties of the study site and/or study scale (Wang et al., 2011).

According to Barraclough et al. (2010) there are two main pathways of improving NUE: (i) breeding genotypes with high NUE and (b) better N management. Breeding genotypes with high NUE trait would enable higher recovery of N from the soil while increasing or maintaining grain yield with less N fertilizer. For the purpose of enhancing NUE, conventional breeding methods rely heavily on grain yield as a selection trait. However, such an approach requires considerable amount of labor, effort and time (Loss and Siddique, 1994). Destructive sampling in the conventional breeding method consists of measuring plant biomass at different crop growth stages. Regan et al. (1992) reported that it is practical only where the number of samples or plots involved is small.

Remote sensing has become an important tool for measuring variability in crop canopies. Many studies have reported Normalized Difference Vegetation Index (NDVI) as a useful tool to collect information from crop canopies for predicting yield, photosynthetic efficiency, green biomass, and leaf area index (Aparicio et al., 2000, 2002; Raun et al., 2001). Active remote sensing tools such as Greenseeker® measure NDVI using light reflected from the crop canopy and can be used to detect variability in biomass and N in crop canopies without destructive sampling (Elliott and Regan, 1993; Inman et al., 2005). The NDVI is calculated as:

$$NDVI = NIR - R / NIR + R, \qquad \text{Eq.1}$$

where R is the reflectance in the red band (wavelengths 600 to 720 nm) and NIR is the reflectance in the near-infrared band (wavelengths 720-1300 nm) (Inman et al., 2005).

Marti et al. (2007) found NDVI to be well correlated to the yield and wheat biomass at milk-grain stage (stage 11 of the Feekes scale) (Large, 1954). Ma et al. (2001) reported that NDVI can differentiate genotypes with high and low yield. Raun et al. (2001) reported a positive relationship ($R^2 > 0.50$) between in-season NDVI estimated yield and measured grain yield in wheat. Likewise, Inman et al. (2007) observed a positive relationship ($R^2 = 0.65$) between NDVI and grain yield in maize. The NUE was improved by more than 15% by using Greenseeker® active remote sensing to better target inputs in wheat crop, suggesting NDVI as a potential screening index for NUE (Raun et al., 2002; Reynolds et al., 2001). Likewise, Araus et al. (2001) showed that a spectral vegetation index such as NDVI is a promising tool to screen genotypes. However, review of literature indicates no previous studies conducted on the topic of identifying and differentiating winter wheat genotypes for their NUE based on data collected from active remote sensing devices. Also, no previous study was conducted to verify if NDVI could characterize variability of winter wheat genotypes based on their NUE.

The hypothesis of this study is that NDVI measured by active sensors can identify and differentiate variation in NUE across wheat genotypes. The objectives of this study were (i) to identify and quantify the main sources of variation in NUE across wheat genotypes and (ii) to determine if NDVI could characterize variability in NUE across wheat genotypes.

MATERIALS AND METHODS

Study sites

This study was conducted in northeastern Colorado over two winter wheat growing seasons, 2009-2010 and 2010-2011 referred to as site years I and II respectively. The study was located at the USDA-ARS Limited Irrigation Research Farm, near Greeley, Colorado (40˚ 26′ 58.87″ N and -104˚ 38′22.56″ W). Both site years were under drip irrigation, and soils were mapped as Otera sandy loam (coarse–loamy, mixed superactive, calcareous, mesic Aridic Ustorthents) soil series with zero to three percent slope (Crabb, 1980). The soils were deep, well-drained and were formed by eolian deposits and mixed outwash parent material and included loam and clay loam underlying material. In site year I (2009-2010), the total precipitation received during the crop growing season from October 1, 2009 to July 31, 2010 was 292.9 mm. For site year II (2010-2011), the total precipitation received from October 1, 2010 to July 31, 2011 was 209.3 mm (USDA, 2012). The total precipitation received during the two site years was higher than the ten years average precipitation of 170.6 mm for the same time periods. The previous crop was dry (pinto) beans (*Phaseolus vulgaris* L.) under dryland and irrigated conditions for both years.

Experimental Procedure

A global positioning system unit was used to map the field boundaries and to geo-reference soil samples (Trimble Ag 114 GPS antennae with differential correction, CA, USA). Soil samples were collected using a systematic unaligned grid sampling design for the entire study area in both site-years. Thirty soil samples were collected at two depths, 0 - 20 cm and 20- 61 cm, at 15 locations within the 0.2 hectare study area (i.e. a sampling density of 72 samples per). Soil samples consisting of several soil cores were collected from each depth to obtain one composite soil sample. Soil samples were dried and sent to a commercial laboratory (Ag Source Harris Lab., Lincoln, NE) for chemical and physical soil property analysis. Particle size analysis was determined by using the hydrometer method (Gee and Bauder, 1986). Soil pH was measured using 1:1 water to soil slurry (Thomas, 1996). Organic matter (OM) was determined using the loss on ignition method (Heiri et al., 2001). Soil NO_3-N was measured using the cadmium reduction method (Mulvaney, 1996). A Moran's I analysis was used to asses spatial autocorrelation of soil parameters. A summary of soil properties for both sampling depths across the two site years is presented in Table 2.2.

Table 2.2 Summary of soil properties for soil samples acquired at depths of 0-20 cm and 20-61 cm. Soil NO_3-N contents were determined on samples collected on March 22nd (at early spring) and August 19th of 2010 (after harvest) for site year I and November 8th 2010 (at early fall) and August 22nd 2011(after harvest) for site year II.

Site year	Sampling depths (cm)		pH	O.M %	N at early spring Mg g^{-1}	N after harvest Mg g^{-1}	Sand %	Silt %	Clay %	Soil texture
I	0-20	Min	7.9	1.0	22.0	5.0	64.8	13.6	9.6	Sandy Loam
		Mean	8.0	1.1	31.0	7.9	68.4	16.5	15.1	
		Max	8.1	1.3	47.0	14.0	72.8	21.6	17.6	
	20-61	Min	7.9	0.9	11.0	5.0	60.8	13.6	11.6	Sandy Loam
		Mean	8.0	1.1	22.3	12.5	67.7	16.9	15.3	
		Max	8.2	1.3	40.0	37.0	72.8	21.6	17.6	
Site year	**Sampling depths (cm)**		**pH**	**O.M %**	**N at early fall Mg g^{-1}**	**N after harvest Mg g^{-1}**	**Sand %**	**Silt %**	**Clay %**	**Soil texture**
II	0-20	Min	7.8	1.0	30.0	8.0	58.8	4.4	12.8	Sandy Loam
		Mean	8.0	1.2	38.0	15.4	64.9	16.7	18.4	
		Max	8.1	1.5	54.0	22.0	70.8	24.4	30.8	
	20-61	Min	8.0	0.8	16.0	4.0	53.2	3.6	15.2	Sandy Loam
		Mean	8.2	1.0	22.4	9.8	61.7	17.7	20.5	
		Max	8.4	1.3	44.0	22.0	67.2	27.6	29.2	

This study was a part of a large ongoing multi-disciplinary project. The main experimental design for the large multi-disciplinary project was a split plot design. The data used in the study was analyzed as randomized block design, where the blocks are the replications and the experimental units are the 24 wheat genotypes. Site years and irrigation methods (dryland and irrigated conditions) were analyzed separately. Water application in the irrigated conditions was done based on climatological estimates of crop water use and evaporative demand. Twenty-four winter wheat genotypes were planted under both irrigated and dryland conditions. The genotypes were: Above, Ankor, Arlin, Avalanche, Baca, Bill Brown, Bond CL, CO940610, Danby, Goodstreak, Hatcher, Jagalene, Jagger, Keota, NuDakota, Platte, Prairie Red, Prowers 99, Ripper, RonL, Sandy, Snowmass, TAM 112, and Yuma. Dimensions of individual experimental plots were 3.7 m x 1.4 m with 6 plant rows at spacing of 22.8 cm between each row. Site years I and II were planted on October 11th, 2009 and October 8th, 2010, respectively, at a rate of 197,600 seeds ha^{-1}. Nitrogen and phosphorus fertilizers were applied prior to planting on September 29th, 2009 and October 7th, 2010 under dryland and irrigated conditions for site year I and II respectively. Nitrogen dry fertilizer was applied at a rate of 84 and 112 kg N ha^{-1} as Urea (46-0-0) and phosphorous dry fertilizer was applied at a rate of 56 and 44.8 kg P_2O_5 ha^{-1} as Mono-Ammonium Phosphate (11-52-0) for site year I and II respectively. Also, liquid Ammonium Phosphate was applied at rate 46.8 liter ha^{-1} (10-34-0) with wheat seed as a starter.

Crop biomass samples were collected five times during the growing season at various crop growth stages referred to as: early spring, jointing, anthesis, mid grain filling and maturity. The early spring stage corresponds to the Feekes growth stage of 3 to 4 (tillers formed-leaf-sheaths lengthen), and jointing stage corresponds to the Feekes growth stage 6 (first visible node of stem). The anthesis stage corresponds to the Feekes growth stage 10.5 (flowering); the mid grain filling stage corresponds to the Feekes growth stage 11.1 (milky ripe), and the maturity stage corresponds to the Feekes growth stage 11.4 (ripe for cutting and dead straw) (Large, 1954). Crop biomass samples consisted of 0.5 m row length acquired from each plot. Harvest biomass samples were determined with a 1 m row length and were taken from the middle of the experimental plot. Biomass samples were pulled up, bagged, and transferred to a cooler and stored at 4 ^{o}C until processed. Plants were freed from their roots and were placed into an oven to dry at about 68 ^{o}C until they reached a constant weight. Approximately ten to fifty plants were used per plot and then total aboveground biomass samples weighted, grinded, and analyzed to identify total N in crop tissue. The variation in the number of plants per sample across plots was due to taking a fixed length of row (0.5 m for all biomass samplings except at maturity when a 1-m length of row was sampled) as opposed to a fixed number of plants. The plots were harvested by plot combine in June 28th under dryland and July 6th under irrigated for site year I. For site year II plots were harvested in June 28th under dryland and July 7th under irrigated to measure grain yield and protein percentage in grains (measured using near-infrared method for protein content in whole-grain wheat) was corrected to 12% moisture.

Nitrogen use efficiency (NUE)

Partial factor productivity (PFP) and partial nitrogen balance (PNB) were the two measures of NUE that were employed in this study. The PFP was calculated as kg of grain per kg of N supplied (Nielsen, 2006; Snyder and Bruulsema, 2007). The PNB was calculated as kg of grain N content per kg of N supplied (Hawkesford, 2012; Snyder and Bruulsema, 2007). Nitrogen use efficiency and related parameters are explained in Table 2.3 (Nelson et al., 2012; Snyder and Bruulsema, 2007).

Table 2.3 Measurements and calculations of nitrogen use efficiency and related parameters (Nelson et al., 2012; Snyder and Bruulsema, 2007).

Measurement	Acronym	Calculation (kg)
Partial Factor Productivity	PFP	Grain / N supplied
Partial N Balance	PNB	Grain N content$*$ / N supplied
Nitrogen uptake efficiency	UPE	$\frac{Total\ N\ in\ above\ ground\ biomass\ at\ maturity\ **}{N\ supplied}$
Nitrogen utilization efficiency	UTE	$\frac{\text{Grain}}{\text{Total N in above ground biomass at maturity}}$
Biomass production efficiency	BPE	$\frac{\text{Aboveground biomass}}{\text{Total N in above ground biomass at maturity}}$
Ratio of grain N content to aboveground biomass weight	GN/BW	Grain N content / Aboveground biomass

$*$ Grain N content = % protein in grain ÷ conversion factor (5.7) x grain yield (kg/ha)

** Total N = grain N content (kg/ha) + plant N content (kg/ha)

Active remote sensing

Active remote sensing based NDVI measurements were acquired using a Greenseeker® Model 505 handheld optical sensor (NTech Industries Inc., Ukiah, California, USA). The principles of operation of the Greenseeker® were illustrated in Inman et al. (2005). The Greenseeker® generates light at two wavelengths: visible red light (R) at 656 ± 25 nm, and near-infrared (NIR) at 774 ± 25 nm (NTech, 2009). The Greenseeker® sensor is referred to as a “red sensor” and it measures light reflected from the plant canopy to calculate the NDVI. The field-of-view of the sensor is about 61cm by 1.5 cm (NTech, 2009). In-field reflectance measurements were taken by holding the Greenseeker® unit about 90 cm above the crop canopy and walking in the center of each wheat plot. Each plot was sensed for approximately two to five seconds, collecting 20 to 50 NDVI readings. The reflectance measurements were acquired weekly between 10:00 am and 2:00 pm on cloud-free days. Readings were collected from early spring wheat growth stage (March 29th, 2010) to after the mid grain filling stage (June 21st, 2010) for site year I, and from March 21st, 2011 to June 27th, 2011 for site year II (Fig. 2.1).

Figure 2.1 The NDVI readings were collecting using Greenseeker® handheld optical sensor. Plot boundaries are highlighted with white dashed lines.

Statistical analysis

Statistical analysis was performed to determine differences among grain yield and NDVI readings for 24 wheat genotypes using analysis of variance (ANOVA) in statistical software R

(R Development Core Team, 2010). Preliminary analysis indicated a significant interaction between the genotypes and plot replication indicating significant site differences across replications. This complicates the interpretation of the results since the response of NDVI to genotype cannot be explained just in terms of the main effects, (i.e.) wheat genotype. Hence, a three-step process was used to remove the site effect from the data prior to statistical analysis. The first step was to remove the effect of genotype from the NDVI readings. This was accomplished by a regression analysis of NDVI data against genotypes using a general linear model (GLM). The residuals from the GLM represent the site effect. The next step was to characterize the spatial structure of the residuals using a semi-variogram. An empirical semi-variogram was fit to several theoretical variogram models (e.g., Gaussian, exponential and spherical) using the method of least squares. The variogram model that minimized the Akaike information criterion AIC was selected to estimates the site effect for each observation in the data using simple kriging. The final step was to subtract the estimated site effect from the observed raw data. This adjusted data set was then analyzed using ANOVA to test for the significance of genotype and replication effects. When no significant interaction between genotypes and replication was observed, the approach was deemed to be successful. Pairwise comparisons were made among genotypes using Tukey honestly significant difference test.

The N uptake efficiency (UPE) and N utilization efficiency (UTE) were considered as the two main factors contributing to PFP while biomass production efficiency (BPE), N uptake efficiency (UPE) and ratio of grain N content to aboveground biomass weight (GN /BW) were considered as the three main factors contributing to PNB (Van Sanford and MacKown, 1986). The contribution to NUE from each parameter was determined by the method of Moll et al. (1982). If log PFP = Y_1, log PNB = Y_2, log UPE = X_1, log UTE = X_2, log BPE = X_3

and log GN/BW = X_4, then

$$Y_1 = X_1 + X_2, \text{ and} \qquad \text{Eq.2}$$

$$Y_2 = X_1 + X_3 + X_4. \qquad \text{Eq.3}$$

The proportion of the sum of squares for Y_j to the related parameter (X_i) is:

$$Cov(x_i y_j)/S_{y_j}^2 = r_{x_i y_j} \times S_{x_i}/S_{y_j}, \qquad \text{Eq.4}$$

where $Cov(x_i y_j)$ is the covariance between Y_j and X_i, $S_{y_j}^2$ is the variance of Y_j, $r_{x_i y_j}$ is correlation coefficient between Y_j and X_i, and S_{x_i} and S_{y_j} are the standard deviations of X_i and Y_j respectively.

The linear association between NDVI and either UPE, UTE, BPE or GN/BW was determined by using Pearson's product-moment correlation coefficient (r) between PFP or PNB and UPE, UTE, BPE and GN/BW. In addition, a power function was used to model the relationship between PFP and PNB and NDVI:

$$y = Ax^B, \qquad \text{Eq. 5}$$

where *y* is PFP or PNB, *A* and B are the model parameters and *x* is the NDVI value. The coefficient of determination (R^2) was used to explain the proportion of variability in PFP or PNB explained by variation NDVI.

RESULTS AND DISCUSSION

Nitrogen use efficiency across wheat genotypes

For site-year I, statistical analysis of variance (ANOVA) did not show significant differences among 24 wheat genotypes based on PFP and PNB under both dryland and irrigated conditions (Appendix B. Table. B.1-4). Under dryland conditions, the mean PFP ranged from 31.41 to 65.03 kg of grain yield per kg of N supplied (Fig. 2.2) and the mean PNB ranged from 0.76 to 1.55 kg of grain N content per kg of N supplied (Fig. 2.3). Under irrigated conditions, the mean PFP ranged from 71.27 to 96.38 kg of grain yield per kg of N supplied (Fig. 2.2), and the mean PNB ranged from 1.41 to 1.94 kg of grain N content per kg of N supplied (Fig. 2.3). For site-year II ANOVA results showed significant differences among the twenty four wheat genotypes ($p<0.05$; Appendix B. Table. B.5-8) based on PFP and PNB under both dryland and irrigated conditions. In dryland conditions, the mean PFP ranged from 25.79 to 38.09 kg of grain yield per kg of N supplied (Fig. 2.4) and the mean PNB ranged from 0.65 to 0.95 kg of grain N content per kg of N supplied (Fig. 2.5). Under irrigated conditions, the mean PFP ranged from 59.06 to 82.24 kg of grain yield per kg of N supplied (Fig. 2.4) and the mean PNB ranged from 1.47 to 1.89 kg of grain N content per kg N supplied (Fig. 2.5).

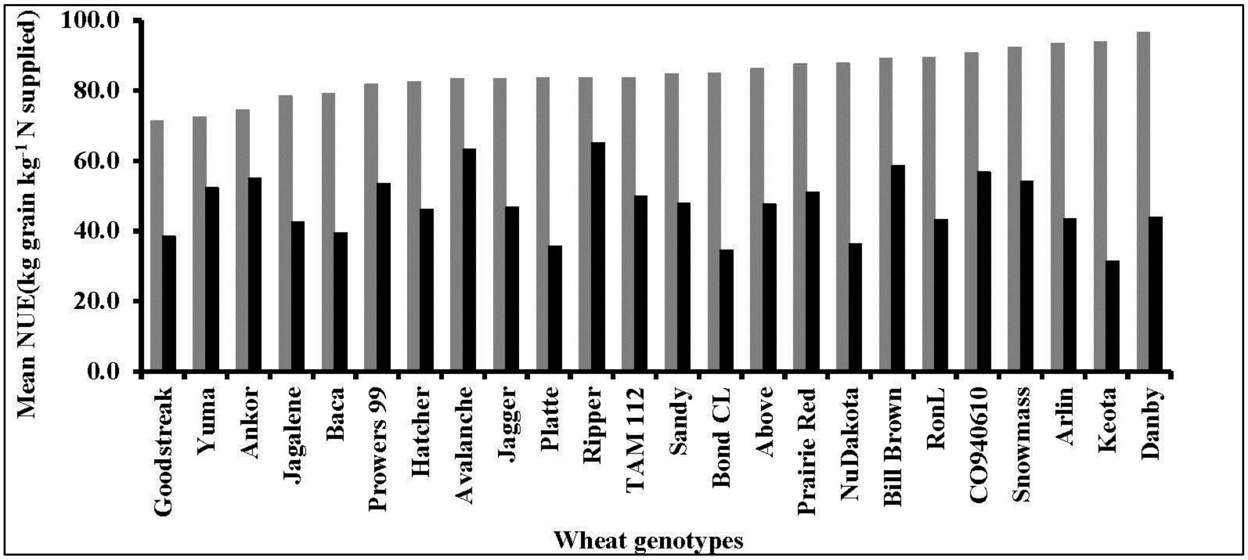

Figure 2.2 Mean nitrogen use efficiency as partial factor productivity (PFP) across 24 winter wheat genotypes. Black and gray bars represent NUE for wheat genotypes under dryland and irrigated conditions respectively, for site year I.

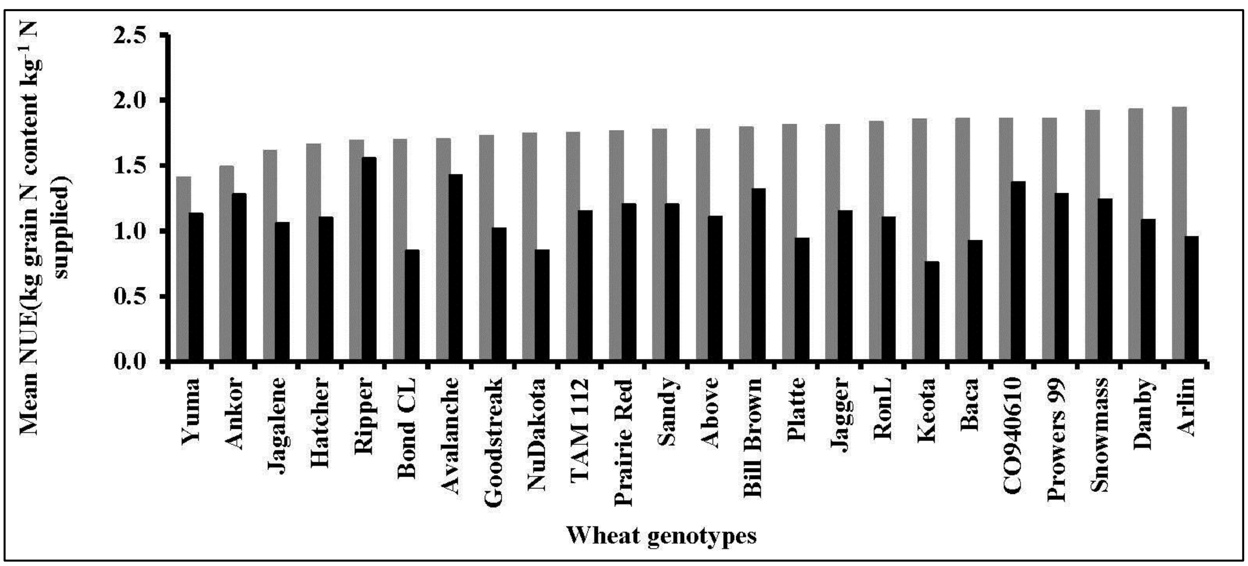

Figure 2.3 Mean nitrogen use efficiency as partial factor productivity (PFP) across 24 winter wheat genotypes. Black and gray bars represent NUE for wheat genotypes under dryland and irrigated conditions respectively, for site year I.

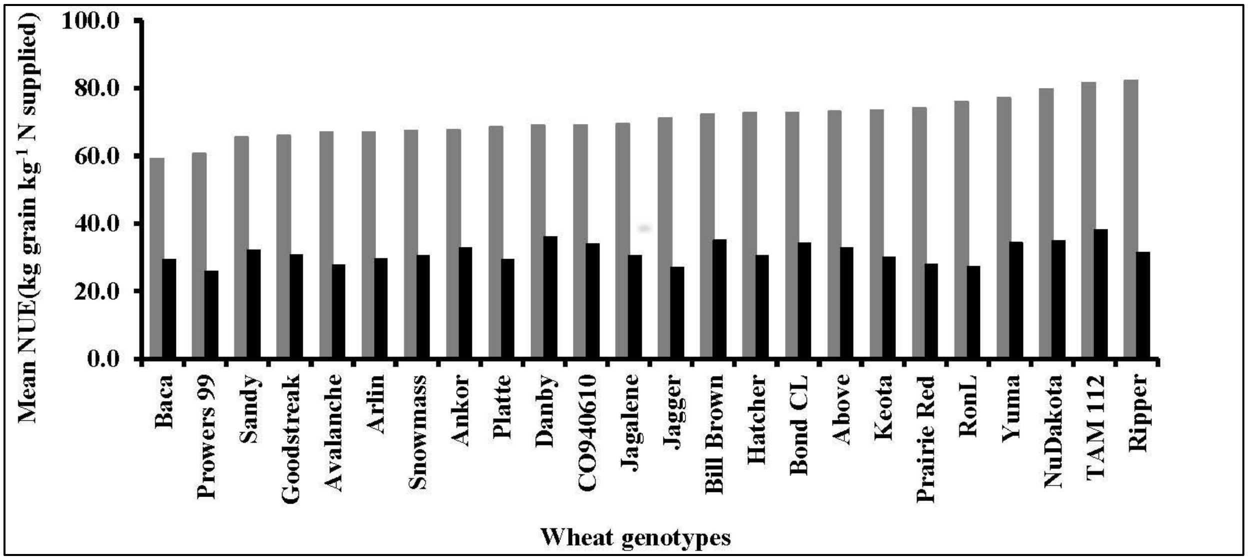

Figure 2.4 Mean nitrogen use efficiency as partial factor productivity (PFP) across 24 winter wheat genotypes. Black and gray bars represent NUE for wheat genotypes under dryland and irrigated conditions respectively, for site year II.

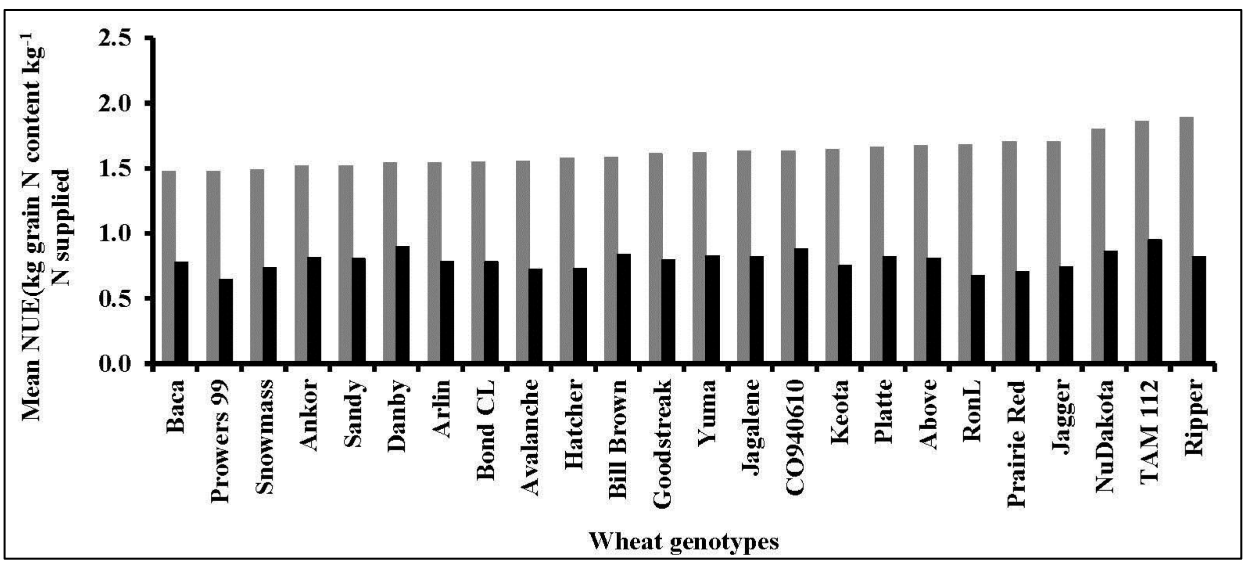

Figure 2.5 Mean nitrogen use efficiency as partial nitrogen balance (PNB) across 24 winter wheat genotypes. Black and gray bars represent NUE for wheat genotypes under dryland and irrigated conditions respectively, for site year II.

Significant differences in PFP and PNB among wheat genotypes were expected for both site years. We hypothesized that a pool of 24 different genotypes would perform differently under dryland and irrigated conditions. Consistent with our findings, Van Sanford and

MacKown (1986) observed significant differences in NUE in a pool of 25 wheat genotypes. The absence of significant differences in NUE for site year I, despite a large range of PFP and PNB, was related to a large sum of squares of the residuals as compared to that of genotype and replication effects. This implies that most of the effect on PFP and PNB values was explained by factors other than genotype and replication. Among the possible sources of variation are the residual N in soil at the beginning of the season in site year I, which ranged from 22 to 47 Mg g^{-1} in surface (0 to 20 cm) and from 11 to 40 Mg g^{-1} in deeper soil horizon (20 to 61 cm). Based on Moran's I, there was no spatial autocorrelation in N values at both depth, even though the samples were collected at an average nearest neighbor distance of 14.2 m. In addition, examination of soil analysis results show that soil sulfur (S) content ranged from 47 to 345 Mg g^{-1} (data not shown in Table 2.2) and again, Moran's I analysis did not reveal spatial autocorrelation for sulfur either. This implies that the spatial range of both N and S was shorter than 14.2 m and would not have characterized the spatial variability of these two important nutrients for NUE. The NUE was increased when S supplied at high N rate, thus illuminating a synergism between N and S (Salvagiotti et al., 2009). Conversely, in site year II, the genotype and replication effects explained most of the variation in PFP and PNB. The PFP and PNB values were higher in irrigated conditions than in dryland conditions, most likely because yields were limited by water, which limited NUE (McMaster et al., 1994). Incidentally, in dryland conditions, the N fertilizer supplied to the plants was perhaps less efficiently taken up and/or utilized, which translated to lower yield. While, the N fertilizer supplied to the plants was perhaps more efficiently taken up and/or utilized in irrigated conditions, which translated to higher yield. This could have affected both PFP and PNB that are calculated based on N fertilizer supplied. Likewise, the PFP and PNB in site year I were significantly higher ($p<0.05$)

than PFP and PNB in site year II. This can be attributed to both higher rainfall and a lower N rate (i.e. 28 kg ha^{-1} less) in site year I. Gauer et al. (1992) have observed a negative relationship between N supplied and NUE and a positive relationship between moisture supplied and NUE, which is consistent with our findings.

Sources of variation of NUE across wheat genotypes

In first instance, we observed a strong correlation between PFP and PNB: a correlation coefficient of 0.97 for site year I and 0.98 for site year II under dryland conditions and a correlation coefficient of 0.85 for site year I and 0.92 for site year II under irrigated conditions. Van Sanford and MacKown (1986) also reported that PFP was highly correlated with PNB in 25 winter wheat genotypes. Both PFP and PNB were divided by N supplied and thus, their high correlation indicated a high correlation between grain N content and grain yield. This is in concordance with the positive correlation between grain yield and grain N content (Heitholt et al., 1990; Triboi et al., 2006). However, Triboi et al. (2006) reported a negative correlation between yield and grain N concentration (as opposed to grain N content), which we also observed and is consistent with most reports in the literature (Heitholt et al., 1990; Simmonds, 1995). The negative correlation between yield and grain N concentration can be explained by a biological loss in carbohydrates due to protein fixation in grain, which comes in competition with yield (Penning De Vries, 1974, 1975).

When considering the contribution of the different NUE parameters (UTE, UPE, BPE and GN/BW), we observed different patterns between site year I and site year II and between irrigated and dryland conditions (Table 2.4). Our results show that UPE was the dominant factor in site year I under irrigated conditions while in site year II it was the dominant factor under dryland conditions (Table 2.4). Soil moisture (i.e. precipitation and irrigation) effect alone cannot explain this pattern because both patterns (i.e. UPE dominant and UPE in the same proportion as the other parameters) were observed under irrigated conditions. Neither N rate effect alone can explain these patterns since each site year, which had different N rates, show both types of pattern. These patterns seems to be related to grain yield that was significantly higher ($p<0.05$) in site year I than in site year II under dryland conditions, but significantly lower ($p<0.05$) in site year I than in site year II under irrigated conditions. Our results thus indicate that when conditions were less conducive to yield, the genotypes that had a higher capacity to uptake N were the ones that achieved a higher NUE. However, when conditions were more conducive to yield, UPE was important in the same proportion as either UTE (for PFP) or GN/BW (for PNB) to achieve a higher NUE. These observations are consistent with the results of Dhugga and Waines (1989) and Tong et al. (1999) who attributed the relative importance of UPE to explain NUE variations to an increasing N rate. Our results show that N rate does not seem to be the major factor influencing the importance of UPE for the variations in NUE, but rather yield. Few studies have reported effects other than N rate to explain the importance of UPE for the variations in NUE. Baresel et al. (2008) observed a strong effect of environment (location x year) on the importance of UPE for the variations in NUE. It is thus possible that, even though environmental factors such as temperature, diseases, weeds or soil fertility were not systematically monitored in this study, they could have impacted the relative importance of UPE to explain NUE. This may explain divergent results such as the one from Ortiz-Monasterio et al. (1997) who reported that NUE was explained in large proportion by UPE at low N level and by UTE at high N level in wheat.

Table 2.4 Contribution of parameters related to the variation in PFP and PNB.

		Dryland		Irrigated	
		Site year I	Site year II	Site year I	Site year II
Traits	Log	$r_{x_i y_j}$[†] S_{x_i}/S_{y_j}[§]	$r_{x_i y_j}$ S_{x_i}/S_{y_j}	$r_{x_i y_j}$ S_{x_i}/S_{y_j}	$r_{x_i y_j}$ S_{x_i}/S_{y_j}
PFP	$\mathbf{Y_1}$	-	-	-	-
UPE	X_1	0.52	0.86	0.88	0.46
UTE	X_2	0.48	0.14	0.12	0.54
PNB	$\mathbf{Y_2}$	-	-	-	-
UPE	X_1	0.62	0.91	0.93	0.60
BPE	X_3	-0.10	-0.25	-0.38	-0.08
GN/BW	X_4	0.48	0.34	0.47	0.49

† $r_{x_i y_j}$ is correlation coefficient between Y_j and X_i

§ S_{x_i} and S_{y_j} the standard deviations for Y_j and X_i

PFP: Partial factor productivity; UPE: Uptake efficiency; UTE: Utilizes efficiency; PNB: Partial nitrogen efficiency; BPE: Biomass production efficiency; GN/BW: Grain nitrogen content / above ground biomass.

We observed a negative contribution of biomass production efficiency (BPE) to the variation in PNB (Table 2.4). This observation was related to negative correlation between BPE and PNB in both site years and under dryland and irrigated conditions. When there was a strong negative correlation between BPE and PNB, it translated into a strong negative contribution of BPE to variation in PNB. Negative correlation was thus related to the intensity of the correlation between the different components of BPE calculation. In PNB calculation, kg of grain N is the numerator and kg of N supplied is the denominator (constant) while in BPE, kg of above ground biomass is the numerator and kg of total N in aboveground biomass at maturity is in the denominator (see Table 2.3). We have observed that when there was a strong positive correlation between kg N in grain and kg of total N in above ground biomass at maturity. Also, we observed a weaker positive correlation between kg of above ground biomass and kg of total

N in above ground biomass at maturity, this translated into a stronger negative BPE contribution to PNB. Conversely, when both previously mentioned correlations were of the same intensity, this translated into a weaker negative contribution of PBE to variation in PNB. A positive correlation between kg N in grain and kg of total N in above ground biomass was observed by Neales et al. (1963) and Cox et al. (1985) for both low and high N rates. Also, a strong positive correlation between kg of above ground biomass and kg of total N in above ground biomass was observed by Jensen et al. (1990). In regards of the later reported correlations, this would translate into a weak BPE contribution to PNB.

In general, the correlation between NUE and parameters related to NUE (i.e. UPE, UTE, BPE and GN/BW) were proportional to their respective contribution to variation in PFP or PNB in Table 2.4. This can be explained by the correlation observed between these parameters, that is part of the calculation in the method of Moll (Eq. 4; Moll et al., 1982). For instance, a strong significant correlation coefficient was observed between UPE and PFP; 0.75 and 0.96 for site year I and II respectively under dryland conditions and 0.68 and 0.50 for site year I and II respectively under irrigated conditions. Also, a high negative correlation was observed between BPE and PNB; -0.16 and -0.55 for site year I and II respectively under dryland conditions and -0.37 and -0.08 for site year I and II respectively under irrigated. The same pattern was observed for the other parameters related to NUE (i.e. UTE and GN/BW). Thus, the results from the correlation were reflected in the contribution of the NUE related parameters to the PFP or PNB variation (Table 2.4).

Nitrogen uptake efficiency thus appears as an important contributing factor to the variation in PFP and PNB among the 24 wheat genotypes in this study. However, environmental factors impacting yield seem to impact the relative importance of UPE over other parameters related to NUE (i.e. UPE, UTE, BPE and GN/BW). Environmental factors were not systematically monitored for the scope of this study, but remain an important aspect to consider for further research on nitrogen use efficiency across wheat genotypes.

Characterization of the NUE variability across wheat genotypes using NDVI

Figure 2.6 illustrates the relationship between r square (of the regression between NDVI and PFP or PNB) and the day of the year (DOY). The time-series of r square for PFP to NDVI regression and the time-series of r square for PNB to NDVI regression nearly overlapped for both site years and conditions. This is consistent with the high correlation between PFP and PNB mentioned above and it indicates that NDVI performed equally well to estimate PFP (based on kg of grain) and to estimate PNB (based on kg N in grain).

Lower r square was observed in mid-season under dryland for site year I and under irrigated conditions for both site years, possibly related to saturation in NDVI (Fig. 2.6). Large amount of green biomass induces NDVI saturation, which lowers the distinguishing power of NIDV for biomass variations, resulting in a lower r square. Saturation of NDVI happens when there is enough chlorophyll in the field of view of the sensor to absorb almost all (about 97%) of the red light (Aparicio et al., 2002; Serrano et al., 2000). Further details about this subject can be found in Chapter 1 of this thesis. Irrigated conditions produced larger amounts of biomass and thus more chlorophyll content, which lead to NDVI saturation early in the season and low r square for both years. In this context, a higher r square would be expected in the earlier growth stages, before crop canopy closure. However, early growth stages corresponded to the period of the season when the variance in NDVI was the lowest and thus genotypes did not show distinct variations in canopy under irrigated conditions. This is consistent with the high variance in NDVI observed in dryland conditions as compared to the variance in NDVI observed in irrigated conditions. Because of a lower variance, the model predicting PFP and PNB based on NDVI values showed a better performance in dryland than in irrigated conditions. Low r square in the mid-season under dryland conditions in site year I was potentially related to a large precipitation event (61.21 mm of rain over eight days from DOY 112 to DOY 120), which produced more biomass and more chlorophyll content due to absence of moisture stress symptoms. These conditions potentially lead to NDVI saturation the same way it did for irrigated conditions. After the precipitation event, moisture stress symptoms returned, which would explain the return to higher r square values after DOY 130. These observations confirm the potential of NDVI to detect wheat genotypes with higher NUE in dryland conditions. In irrigated (or in geographic locations with sufficient precipitation) conditions and in above than average rainfall for dryland conditions, the potential of NDVI measured with Greenseeker® sensor to detect wheat genotypes with higher NUE is limited due to saturation of the NDVI index. In these situations, better potential will be at early and late growth stages when NDVI measured with Greenseeker® sensor does not saturate.

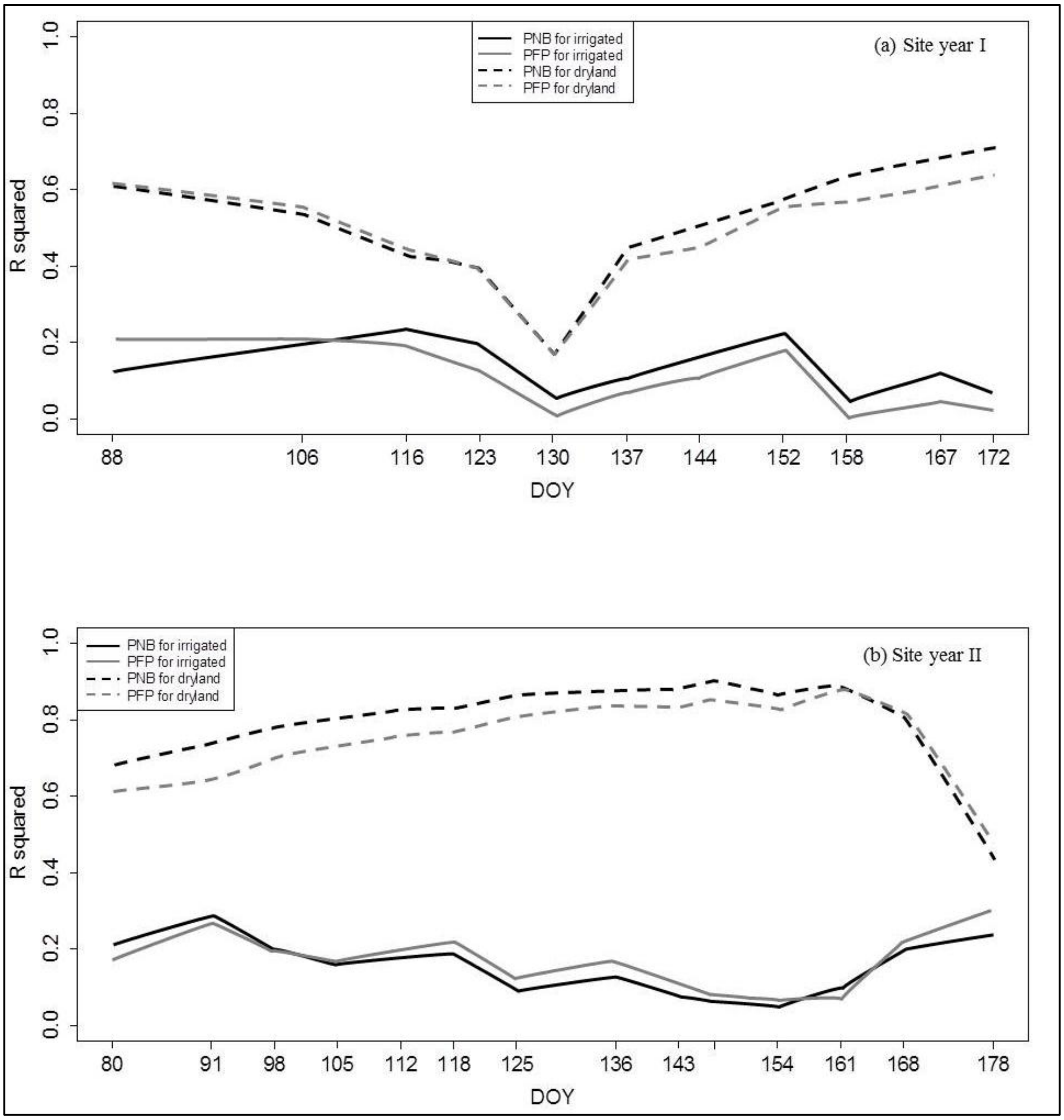

Figure 2.6 Relationship of the r squared value between NDVI and PFP and PNB with day of year (DOY) across 24 winter wheat genotypes under dryland and irrigated conditions for (a) site year I and (b) site year II.

Our results confirm our hypothesis according to which the potential of using NDVI measured by active sensors such as Greenseeker® sensor can identify and differentiate variation in NUE across wheat genotypes. There was a significant difference in NUE across wheat genotypes and a high correlation between NDVI and NUE (PFP and PNB) under dryland conditions.

One of the main outcomes of this study is the importance of UPE to achieve higher NUE for wheat when environment conditions are less conducive to yield and it's less important when environment conditions are more conducive to yield. This information could be used to improve overall NUE via precision nutrient management of a field showing spatial variability in yield potential. For example, with the recent advent of split planters (i.e. planters allowing the switch from one variety to another on-the-go) a farmer could decide to plant genotypes with high UPE trait in low productivity zones while planting genotypes with a more balanced UPE to UTE ratio trait in the high productivity zones of the field. This is still conceptual because the environment factors influencing the relative importance of UPE to explain NUE were not identified in this study. The second main outcome of this study is the determination of the limitations of NDVI index associated with saturation for the prediction of wheat NUE. Our results have shown that NDVI is a good index for prediction of NUE in sparse canopy but not necessarily in dense crop canopy. Based on these results, plant breeders can make a better use of NDVI index by using active crop canopy sensors to predict NUE in dryland conditions, trying to avoid mid-season, especially after big rain events. We believe that NDVI measurements are not suited for irrigated conditions because high soil moisture reduces the variance among genotypes early in the season, thus reducing the discrimination power of NDVI. Irrigated conditions also generate a dense closed canopy early in the season, as compared to growth in dryland conditions, inducing NDVI saturation and again, reducing the discrimination power of NDVI.

Further research could be done in order to further improve correlation between NDVI and NUE under different environment conditions to overcome the limitations of NDVI saturation. For instance, the NDVI index used in this study was based on red band (at 656 nm), which corresponds to the lowest reflectance values (about 3 % of incident light) in the visible spectrum

(Aparicio et al., 2002). This induces saturation as soon as the sensor detects dense healthy crop canopy. It is possible that if the NDVI was based on wavebands before or after the red band, it could be more sensitive to variations in a healthy crop canopy. Hence, it is possible that an index based on another waveband (e.g. red edge around 700 nm) could potentially result in higher correlation than what we have observed in irrigated conditions. Another interesting possibility for the improvement of the NDVI use for NUE prediction would be to modelize the parameters of the power model (i.e. values for A and B from Eq. 5) over time (Feekes growth stages). This would provide the best model parameters to convert NDVI into NUE at any growth stage and thus increase the versatility and accuracy of this tool.

CONCLUSION

Active remote sensing based on NDVI was used as a tool to characterize and differentiate 24 wheat genotypes based on their nitrogen use efficiency. The results of this study partially supported our hypothesis that NDVI measured by active sensors can identify and differentiate variations in nitrogen use efficiency across wheat genotypes. Significant differences in nitrogen use efficiency among the 24 wheat genotypes were observed. Nitrogen uptake efficiency was identified as the main source of variation among genotypes for high nitrogen use efficiency in site-years with lower yield. When overall yield was higher, nitrogen uptake efficiency was as important as the nitrogen utilization efficiency (for partial factor productivity) or as the ratio of grain N content to aboveground biomass weight (for partial nitrogen balance). A strong relationship between NDVI and nitrogen use efficiency across the 24 wheat genotypes under dryland conditions was observed. The results also suggest that because of NDVI saturation, NDVI could not accurately predict nitrogen use efficiency under irrigated conditions. More research is needed in future on hardware (different wavebands) as well as on software (prediction model adapted to any growth stage) to further increase the accuracy and versatility of NDVI as a tool to predict wheat nitrogen use efficiency.

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APPENDIX A

Data from chapter1

Table A.1 Analysis of variance for grain yield under dryland conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	2.253	1.1267	0.7509	0.4776
Genotypes	23	39.31	1.7091	1.1391	0.3443
Residuals	46	69.02	1.5004		

Table A.2 Analysis of variance for grain yield under irrigated conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	1.239	0.61965	0.6401	0.5319
Genotypes	23	20.677	0.89901	0.9286	0.5645
Residuals	46	44.533	0.96812		

Table A.3 Analysis of variance for grain yield under dryland conditions for site year II.

	Df	Sum Sq	Mean Sq	F value	Pr (>F) [1]
Rep	2	43.076	21.5382	125.141	2.00E-16***
Genotypes	23	8.626	0.375	2.179	0.01224*
Residuals	46	7.917	0.1721		

Table A.4 Analysis of variance for grain yield under irrigated conditions for site year II.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	47.706	23.853	68.6046	1.57E-14***
Genotypes	23	29.415	1.2789	3.6784	8.40E-05***
Residuals	46	15.994	0.3477		

[1] Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table A.5 Mean NDVI data for site year I under dryland conditions.

Genotypes	Rep	NDVI date1	NDVI date2	NDVI date3	NDVI date4	NDVI date5	NDVI date6
Above	1	0.199	0.399	0.625	0.593	0.698	0.782
Ankor	1	0.187	0.416	0.595	0.621	0.838	0.886
Arlin	1	0.131	0.201	0.354	0.312	0.565	0.665
Avalanche	1	0.212	0.490	0.682	0.781	0.853	0.858
Baca	1	0.134	0.221	0.311	0.342	0.737	0.507
Bill Brown	1	0.190	0.331	0.488	0.433	0.872	0.892
Bond CL	1	0.178	0.371	0.576	0.604	0.821	0.773
CO940610	1	0.222	0.455	0.709	0.738	0.829	0.885
Danby	1	0.152	0.249	0.483	0.467	0.821	0.750
Goodstreak	1	0.184	0.348	0.559	0.587	0.887	0.868
Hatcher	1	0.173	0.326	0.562	0.579	0.892	0.901
Jagalene	1	0.184	0.395	0.615	0.640	0.908	0.884
Jagger	1	0.122	0.187	0.251	0.255	0.756	0.456
Keota	1	0.127	0.175	0.286	0.222	0.597	0.472
NuDakota	1	0.134	0.199	0.279	0.262	0.775	0.645
Platte	1	0.209	0.411	0.575	0.571	0.861	0.781
Prairie Red	1	0.187	0.394	0.636	0.647	0.681	0.864
Prowers 99	1	0.204	0.403	0.533	0.529	0.812	0.795
Ripper	1	0.232	0.476	0.679	0.675	0.764	0.905
RonL	1	0.138	0.209	0.324	0.313	0.691	0.735
Sandy	1	0.157	0.287	0.457	0.437	0.874	0.752
Snowmass	1	0.154	0.298	0.390	0.455	0.744	0.713
TAM 112	1	0.195	0.417	0.649	0.694	0.821	0.837
Yuma	1	0.222	0.453	0.654	0.661	0.669	0.837
Above	2	0.200	0.362	0.532	0.570	0.663	0.801
Ankor	2	0.213	0.399	0.579	0.570	0.764	0.734
Arlin	2	0.204	0.310	0.441	0.412	0.732	0.724

Avalanche	2	0.206	0.407	0.607	0.663	0.759	0.826
Baca	2	0.173	0.322	0.597	0.620	0.681	0.853
Bill Brown	2	0.219	0.406	0.596	0.603	0.758	0.783
Bond CL	2	0.189	0.339	0.514	0.526	0.808	0.750
CO940610	2	0.187	0.322	0.587	0.609	0.825	0.736
Danby	2	0.161	0.295	0.514	0.627	0.849	0.800
Goodstreak	2	0.164	0.268	0.440	0.520	0.719	0.814
Hatcher	2	0.184	0.379	0.573	0.652	0.771	0.798
Jagalene	2	0.194	0.391	0.505	0.499	0.851	0.701
Jagger	2	0.219	0.415	0.603	0.594	0.790	0.821
Keota	2	0.186	0.355	0.555	0.555	0.833	0.801
NuDakota	2	0.168	0.286	0.489	0.493	0.850	0.708
Platte	2	0.181	0.345	0.513	0.523	0.767	0.833
Prairie Red	2	0.173	0.351	0.595	0.636	0.854	0.850
Prowers 99	2	0.187	0.358	0.601	0.611	0.720	0.871
Ripper	2	0.190	0.365	0.646	0.688	0.720	0.883
RonL	2	0.175	0.284	0.534	0.561	0.895	0.811
Sandy	2	0.197	0.405	0.612	0.655	0.803	0.832
Snowmass	2	0.214	0.455	0.710	0.759	0.727	0.891
TAM 112	2	0.178	0.350	0.564	0.581	0.789	0.773
Yuma	2	0.181	0.338	0.535	0.496	0.656	0.731
Above	3	0.193	0.342	0.541	0.491	0.723	0.708
Ankor	3	0.195	0.391	0.592	0.613	0.821	0.819
Arlin	3	0.209	0.434	0.704	0.699	0.780	0.780
Avalanche	3	0.218	0.451	0.686	0.786	0.896	0.855
Baca	3	0.210	0.464	0.763	0.832	0.896	0.912
Bill Brown	3	0.170	0.230	0.318	0.259	0.458	0.700
Bond CL	3	0.187	0.351	0.590	0.576	0.880	0.888
CO940610	3	0.201	0.369	0.605	0.639	0.833	0.845
Danby	3	0.201	0.394	0.553	0.580	0.818	0.749

Goodstreak	3	0.176	0.257	0.363	0.312	0.586	0.704
Hatcher	3	0.200	0.372	0.590	0.593	0.846	0.809
Jagalene	3	0.168	0.235	0.336	0.334	0.695	0.679
Jagger	3	0.192	0.274	0.432	0.385	0.707	0.859
Keota	3	0.180	0.329	0.518	0.546	0.619	0.473
NuDakota	3	0.181	0.351	0.607	0.586	0.766	0.710
Platte	3	0.165	0.216	0.328	0.277	0.429	0.578
Prairie Red	3	0.176	0.249	0.304	0.296	0.773	0.634
Prowers 99	3	0.209	0.392	0.546	0.582	0.774	0.771
Ripper	3	0.225	0.485	0.701	0.774	0.890	0.865
RonL	3	0.213	0.430	0.654	0.708	0.919	0.903
Sandy	3	0.176	0.269	0.377	0.339	0.841	0.677
Snowmass	3	0.176	0.239	0.353	0.283	0.745	0.670
TAM 112	3	0.201	0.379	0.576	0.635	0.839	0.803
Yuma	3	0.180	0.310	0.450	0.391	0.838	0.746

Table A. 5 Continued

Genotypes	Rep	NDVI date7	NDVI date8	NDVI date9	NDVI date10	NDVI date11
Above	1	0.892	0.825	0.588	0.479	0.509
Ankor	1	0.878	0.841	0.657	0.540	0.570
Arlin	1	0.406	0.330	0.375	0.282	0.231
Avalanche	1	0.884	0.850	0.705	0.535	0.560
Baca	1	0.579	0.425	0.534	0.328	0.310
Bill Brown	1	0.869	0.850	0.737	0.581	0.589
Bond CL	1	0.843	0.731	0.606	0.390	0.351
CO940610	1	0.848	0.778	0.652	0.569	0.558
Danby	1	0.780	0.710	0.645	0.580	0.519
Goodstreak	1	0.898	0.839	0.746	0.621	0.656
Hatcher	1	0.836	0.728	0.661	0.485	0.457
Jagalene	1	0.881	0.849	0.711	0.585	0.578
Jagger	1	0.518	0.437	0.504	0.310	0.250
Keota	1	0.461	0.308	0.397	0.372	0.350
NuDakota	1	0.606	0.393	0.527	0.340	0.355
Platte	1	0.782	0.747	0.650	0.464	0.497
Prairie Red	1	0.869	0.800	0.581	0.476	0.420
Prowers 99	1	0.800	0.843	0.746	0.550	0.609
Ripper	1	0.899	0.849	0.636	0.512	0.511
RonL	1	0.672	0.369	0.466	0.357	0.305
Sandy	1	0.806	0.665	0.682	0.496	0.518
Snowmass	1	0.784	0.699	0.578	0.486	0.551
TAM 112	1	0.871	0.840	0.604	0.527	0.570
Yuma	1	0.852	0.828	0.701	0.513	0.525
Above	2	0.791	0.580	0.592	0.519	0.451
Ankor	2	0.745	0.651	0.744	0.712	0.714
Arlin	2	0.624	0.457	0.487	0.489	0.457

Avalanche	2	0.855	0.624	0.672	0.562	0.526
Baca	2	0.723	0.461	0.514	0.478	0.494
Bill Brown	2	0.749	0.649	0.696	0.619	0.634
Bond CL	2	0.647	0.479	0.443	0.368	0.324
CO940610	2	0.713	0.546	0.628	0.584	0.497
Danby	2	0.873	0.617	0.581	0.533	0.503
Goodstreak	2	0.818	0.597	0.631	0.602	0.557
Hatcher	2	0.835	0.646	0.613	0.520	0.502
Jagalene	2	0.706	0.565	0.613	0.499	0.474
Jagger	2	0.760	0.677	0.716	0.639	0.599
Keota	2	0.785	0.615	0.600	0.513	0.452
NuDakota	2	0.750	0.571	0.597	0.617	0.570
Platte	2	0.732	0.461	0.573	0.428	0.386
Prairie Red	2	0.853	0.612	0.614	0.578	0.494
Prowers 99	2	0.823	0.573	0.668	0.557	0.548
Ripper	2	0.851	0.606	0.607	0.567	0.539
RonL	2	0.812	0.627	0.589	0.547	0.494
Sandy	2	0.818	0.656	0.693	0.649	0.659
Snowmass	2	0.881	0.791	0.760	0.715	0.721
TAM 112	2	0.784	0.521	0.462	0.432	0.414
Yuma	2	0.653	0.514	0.513	0.463	0.434
Above	3	0.720	0.505	0.508	0.363	0.301
Ankor	3	0.870	0.773	0.676	0.585	0.627
Arlin	3	0.693	0.586	0.532	0.448	0.426
Avalanche	3	0.915	0.825	0.750	0.699	0.676
Baca	3	0.880	0.844	0.728	0.602	0.595
Bill Brown	3	0.633	0.524	0.536	0.624	0.552
Bond CL	3	0.876	0.702	0.483	0.371	0.304
CO940610	3	0.893	0.853	0.749	0.730	0.684
Danby	3	0.853	0.654	0.662	0.579	0.494

Goodstreak	3	0.682	0.523	0.556	0.527	0.522
Hatcher	3	0.880	0.748	0.660	0.572	0.555
Jagalene	3	0.744	0.618	0.587	0.463	0.434
Jagger	3	0.876	0.744	0.691	0.747	0.723
Keota	3	0.607	0.435	0.435	0.437	0.384
NuDakota	3	0.526	0.531	0.514	0.501	0.429
Platte	3	0.650	0.471	0.431	0.477	0.394
Prairie Red	3	0.785	0.663	0.656	0.671	0.640
Prowers 99	3	0.815	0.730	0.768	0.705	0.694
Ripper	3	0.915	0.844	0.731	0.609	0.616
RonL	3	0.901	0.873	0.746	0.653	0.670
Sandy	3	0.716	0.611	0.599	0.519	0.651
Snowmass	3	0.854	0.592	0.553	0.548	0.568
TAM 112	3	0.891	0.799	0.690	0.631	0.622
Yuma	3	0.777	0.760	0.720	0.640	0.605

Table A.6 Mean NDVI data for site year I under irrigated conditions.

Genotypes	Rep	NDVI date1	NDVI date2	NDVI date3	NDVI date4	NDVI date5	NDVI date6
Above	1	0.186	0.375	0.584	0.664	0.740	0.843
Ankor	1	0.178	0.362	0.521	0.557	0.888	0.789
Arlin	1	0.184	0.362	0.586	0.643	0.854	0.806
Avalanche	1	0.185	0.406	0.622	0.758	0.858	0.878
Baca	1	0.184	0.379	0.594	0.670	0.888	0.885
Bill Brown	1	0.190	0.375	0.596	0.670	0.876	0.862
Bond CL	1	0.185	0.369	0.552	0.552	0.685	0.813
CO940610	1	0.191	0.377	0.592	0.617	0.764	0.835
Danby	1	0.196	0.410	0.621	0.658	0.893	0.881
Goodstreak	1	0.176	0.340	0.566	0.648	0.852	0.887
Hatcher	1	0.195	0.420	0.629	0.696	0.902	0.863
Jagalene	1	0.192	0.439	0.623	0.702	0.830	0.811
Jagger	1	0.194	0.412	0.602	0.679	0.829	0.806
Keota	1	0.197	0.418	0.659	0.747	0.831	0.905
NuDakota	1	0.184	0.361	0.539	0.537	0.709	0.761
Platte	1	0.193	0.435	0.615	0.676	0.793	0.786
Prairie Red	1	0.184	0.411	0.599	0.674	0.761	0.775
Prowers 99	1	0.205	0.436	0.645	0.685	0.755	0.802
Ripper	1	0.201	0.481	0.713	0.764	0.892	0.880
RonL	1	0.179	0.371	0.630	0.669	0.867	0.846
Sandy	1	0.191	0.404	0.623	0.727	0.887	0.891
Snowmass	1	0.193	0.416	0.648	0.733	0.834	0.837
TAM 112	1	0.206	0.468	0.696	0.744	0.806	0.886
Yuma	1	0.208	0.447	0.631	0.682	0.828	0.826
Above	2	0.208	0.416	0.657	0.676	0.846	0.915
Ankor	2	0.188	0.388	0.544	0.560	0.797	0.867
Arlin	2	0.215	0.383	0.617	0.559	0.808	0.847

Avalanche	2	0.218	0.438	0.698	0.738	0.862	0.848
Baca	2	0.227	0.518	0.774	0.849	0.882	0.917
Bill Brown	2	0.231	0.403	0.689	0.704	0.844	0.865
Bond CL	2	0.192	0.371	0.602	0.635	0.878	0.876
CO940610	2	0.208	0.409	0.628	0.630	0.725	0.898
Danby	2	0.226	0.484	0.664	0.728	0.722	0.862
Goodstreak	2	0.209	0.383	0.667	0.697	0.891	0.823
Hatcher	2	0.198	0.352	0.537	0.517	0.641	0.788
Jagalene	2	0.208	0.444	0.638	0.652	0.881	0.835
Jagger	2	0.192	0.333	0.534	0.441	0.698	0.730
Keota	2	0.229	0.407	0.629	0.659	0.762	0.863
NuDakota	2	0.209	0.382	0.666	0.615	0.659	0.788
Platte	2	0.211	0.445	0.671	0.738	0.831	0.836
Prairie Red	2	0.203	0.427	0.628	0.700	0.839	0.907
Prowers 99	2	0.234	0.472	0.630	0.748	0.842	0.913
Ripper	2	0.206	0.420	0.720	0.675	0.815	0.902
RonL	2	0.219	0.437	0.634	0.630	0.850	0.864
Sandy	2	0.198	0.336	0.514	0.517	0.883	0.854
Snowmass	2	0.203	0.427	0.673	0.742	0.878	0.916
TAM 112	2	0.196	0.376	0.620	0.664	0.866	0.899
Yuma	2	0.188	0.313	0.419	0.390	0.627	0.712
Above	3	0.192	0.389	0.624	0.615	0.738	0.870
Ankor	3	0.175	0.291	0.462	0.430	0.662	0.710
Arlin	3	0.196	0.416	0.653	0.610	0.834	0.764
Avalanche	3	0.192	0.430	0.687	0.785	0.881	0.880
Baca	3	0.191	0.366	0.622	0.681	0.881	0.876
Bill Brown	3	0.194	0.411	0.645	0.735	0.903	0.905
Bond CL	3	0.196	0.382	0.578	0.581	0.846	0.888
CO940610	3	0.195	0.357	0.626	0.653	0.824	0.884
Danby	3	0.186	0.422	0.613	0.614	0.844	0.872

Goodstreak	3	0.181	0.340	0.534	0.557	0.813	0.785
Hatcher	3	0.183	0.303	0.478	0.462	0.880	0.850
Jagalene	3	0.200	0.459	0.662	0.759	0.890	0.834
Jagger	3	0.185	0.355	0.545	0.514	0.860	0.906
Keota	3	0.197	0.371	0.567	0.496	0.724	0.750
NuDakota	3	0.198	0.426	0.681	0.668	0.866	0.751
Platte	3	0.170	0.337	0.487	0.420	0.809	0.835
Prairie Red	3	0.184	0.343	0.543	0.598	0.857	0.801
Prowers 99	3	0.207	0.424	0.677	0.741	0.907	0.887
Ripper	3	0.207	0.433	0.691	0.759	0.861	0.898
RonL	3	0.205	0.405	0.615	0.749	0.761	0.880
Sandy	3	0.178	0.383	0.583	0.617	0.870	0.800
Snowmass	3	0.187	0.419	0.687	0.719	0.913	0.893
TAM 112	3	0.199	0.422	0.673	0.696	0.908	0.917
Yuma	3	0.190	0.333	0.531	0.495	0.813	0.773

Table A. 6 Continued

Genotypes	Rep	NDVI date7	NDVI date8	NDVI date9	NDVI date10	NDVI date11
Above	1	0.846	0.834	0.801	0.842	0.771
Ankor	1	0.827	0.797	0.774	0.809	0.764
Arlin	1	0.732	0.762	0.776	0.763	0.731
Avalanche	1	0.865	0.837	0.797	0.812	0.800
Baca	1	0.846	0.821	0.805	0.828	0.812
Bill Brown	1	0.823	0.821	0.774	0.841	0.823
Bond CL	1	0.770	0.803	0.794	0.803	0.772
CO940610	1	0.861	0.797	0.755	0.805	0.762
Danby	1	0.882	0.866	0.788	0.840	0.796
Goodstreak	1	0.888	0.850	0.794	0.847	0.817
Hatcher	1	0.873	0.828	0.813	0.836	0.803
Jagalene	1	0.804	0.789	0.749	0.802	0.745
Jagger	1	0.834	0.821	0.801	0.834	0.799
Keota	1	0.899	0.876	0.752	0.850	0.796
NuDakota	1	0.797	0.764	0.792	0.851	0.782
Platte	1	0.775	0.734	0.798	0.779	0.705
Prairie Red	1	0.837	0.837	0.742	0.813	0.752
Prowers 99	1	0.847	0.748	0.794	0.839	0.825
Ripper	1	0.870	0.842	0.788	0.816	0.764
RonL	1	0.818	0.816	0.817	0.830	0.784
Sandy	1	0.891	0.853	0.821	0.814	0.777
Snowmass	1	0.839	0.810	0.747	0.827	0.804
TAM 112	1	0.885	0.854	0.805	0.827	0.772
Yuma	1	0.823	0.801	0.774	0.805	0.800
Above	2	0.918	0.892	0.808	0.810	0.760
Ankor	2	0.899	0.886	0.807	0.822	0.821
Arlin	2	0.797	0.807	0.764	0.776	0.748

Avalanche	2	0.890	0.863	0.820	0.830	0.791
Baca	2	0.867	0.865	0.810	0.844	0.807
Bill Brown	2	0.849	0.832	0.825	0.850	0.822
Bond CL	2	0.827	0.816	0.790	0.825	0.722
CO940610	2	0.913	0.895	0.810	0.828	0.777
Danby	2	0.924	0.860	0.816	0.839	0.804
Goodstreak	2	0.811	0.843	0.813	0.830	0.783
Hatcher	2	0.747	0.776	0.796	0.762	0.731
Jagalene	2	0.755	0.789	0.817	0.830	0.786
Jagger	2	0.679	0.732	0.831	0.839	0.799
Keota	2	0.840	0.847	0.783	0.815	0.777
NuDakota	2	0.792	0.816	0.817	0.819	0.799
Platte	2	0.834	0.830	0.824	0.809	0.759
Prairie Red	2	0.925	0.886	0.813	0.848	0.772
Prowers 99	2	0.915	0.899	0.833	0.862	0.831
Ripper	2	0.878	0.835	0.812	0.802	0.755
RonL	2	0.879	0.851	0.836	0.854	0.828
Sandy	2	0.767	0.833	0.817	0.817	0.801
Snowmass	2	0.918	0.905	0.801	0.840	0.834
TAM 112	2	0.908	0.852	0.748	0.798	0.735
Yuma	2	0.618	0.628	0.790	0.787	0.764
Above	3	0.852	0.784	0.823	0.792	0.737
Ankor	3	0.531	0.681	0.771	0.751	0.719
Arlin	3	0.678	0.704	0.777	0.764	0.716
Avalanche	3	0.839	0.781	0.818	0.814	0.789
Baca	3	0.848	0.835	0.821	0.819	0.798
Bill Brown	3	0.923	0.875	0.821	0.814	0.806
Bond CL	3	0.897	0.862	0.799	0.792	0.759
CO940610	3	0.890	0.885	0.817	0.804	0.777
Danby	3	0.823	0.804	0.807	0.816	0.763

Goodstreak	3	0.725	0.757	0.807	0.824	0.787
Hatcher	3	0.770	0.709	0.771	0.792	0.747
Jagalene	3	0.813	0.786	0.811	0.818	0.802
Jagger	3	0.907	0.873	0.832	0.832	0.799
Keota	3	0.624	0.734	0.779	0.760	0.716
NuDakota	3	0.728	0.775	0.821	0.799	0.744
Platte	3	0.861	0.793	0.808	0.771	0.713
Prairie Red	3	0.813	0.814	0.791	0.769	0.710
Prowers 99	3	0.883	0.825	0.807	0.856	0.834
Ripper	3	0.902	0.885	0.829	0.813	0.764
RonL	3	0.906	0.864	0.811	0.794	0.755
Sandy	3	0.843	0.800	0.821	0.803	0.770
Snowmass	3	0.866	0.829	0.823	0.835	0.800
TAM 112	3	0.879	0.831	0.803	0.841	0.756
Yuma	3	0.601	0.587	0.742	0.754	0.704

Table A.7 Mean NDVI data for site year II under dryland conditions.

Genotypes	Rep	NDVI date1	NDVI date2	NDVI date3	NDVI date4	NDVI date5	NDVI date6	NDVI date7
Above	1	0.210	0.253	0.267	0.253	0.262	0.235	0.224
Ankor	1	0.163	0.171	0.164	0.164	0.166	0.156	0.150
Arlin	1	0.154	0.160	0.157	0.204	0.189	0.177	0.163
Avalanche	1	0.161	0.170	0.180	0.186	0.205	0.172	0.166
Baca	1	0.191	0.226	0.240	0.247	0.238	0.222	0.210
Bill Brown	1	0.194	0.206	0.212	0.201	0.224	0.198	0.199
Bond CL	1	0.172	0.196	0.202	0.218	0.220	0.203	0.202
CO940610	1	0.188	0.212	0.216	0.227	0.227	0.201	0.207
Danby	1	0.211	0.256	0.278	0.291	0.302	0.273	0.259
Goodstreak	1	0.164	0.181	0.178	0.179	0.196	0.177	0.170
Hatcher	1	0.184	0.210	0.228	0.236	0.251	0.228	0.230
Jagalene	1	0.199	0.252	0.260	0.269	0.289	0.247	0.259
Jagger	1	0.152	0.163	0.160	0.176	0.170	0.157	0.151
Keota	1	0.158	0.165	0.178	0.200	0.208	0.180	0.182
NuDakota	1	0.176	0.193	0.201	0.234	0.227	0.210	0.227
Platte	1	0.189	0.223	0.226	0.237	0.234	0.227	0.207
Prairie Red	1	0.195	0.211	0.227	0.238	0.246	0.219	0.214
Prowers 99	1	0.181	0.193	0.212	0.234	0.252	0.222	0.211
Ripper	1	0.189	0.204	0.227	0.222	0.236	0.213	0.207
RonL	1	0.171	0.188	0.185	0.212	0.207	0.191	0.188
Sandy	1	0.184	0.219	0.232	0.248	0.245	0.220	0.230
Snowmass	1	0.163	0.177	0.180	0.193	0.192	0.181	0.178
TAM 112	1	0.213	0.259	0.254	0.258	0.264	0.233	0.232
Yuma	1	0.155	0.194	0.194	0.199	0.213	0.183	0.196
Above	2	0.255	0.364	0.346	0.410	0.499	0.386	0.391
Ankor	2	0.211	0.281	0.319	0.359	0.419	0.362	0.385
Arlin	2	0.237	0.357	0.385	0.383	0.426	0.386	0.332

Avalanche	2	0.247	0.342	0.370	0.431	0.530	0.450	0.415
Baca	2	0.266	0.373	0.394	0.439	0.527	0.417	0.401
Bill Brown	2	0.232	0.289	0.314	0.331	0.398	0.349	0.339
Bond CL	2	0.229	0.330	0.360	0.430	0.529	0.434	0.443
CO940610	2	0.272	0.326	0.369	0.406	0.515	0.433	0.422
Danby	2	0.271	0.368	0.393	0.386	0.474	0.407	0.376
Goodstreak	2	0.218	0.286	0.291	0.356	0.383	0.323	0.345
Hatcher	2	0.235	0.303	0.348	0.384	0.450	0.394	0.390
Jagalene	2	0.254	0.340	0.399	0.417	0.468	0.434	0.394
Jagger	2	0.232	0.315	0.315	0.383	0.432	0.323	0.330
Keota	2	0.234	0.316	0.353	0.387	0.446	0.376	0.376
NuDakota	2	0.230	0.276	0.302	0.324	0.399	0.338	0.328
Platte	2	0.244	0.320	0.359	0.362	0.423	0.388	0.370
Prairie Red	2	0.231	0.295	0.309	0.355	0.435	0.331	0.341
Prowers 99	2	0.233	0.284	0.299	0.298	0.326	0.297	0.275
Ripper	2	0.322	0.410	0.415	0.408	0.498	0.426	0.367
RonL	2	0.224	0.256	0.263	0.297	0.327	0.291	0.287
Sandy	2	0.246	0.325	0.333	0.372	0.420	0.344	0.341
Snowmass	2	0.215	0.272	0.306	0.354	0.376	0.295	0.294
TAM 112	2	0.238	0.300	0.313	0.345	0.372	0.311	0.305
Yuma	2	0.270	0.351	0.381	0.403	0.528	0.458	0.454
Above	3	0.278	0.407	0.427	0.464	0.564	0.487	0.461
Ankor	3	0.226	0.276	0.320	0.313	0.393	0.374	0.336
Arlin	3	0.263	0.430	0.469	0.513	0.627	0.490	0.458
Avalanche	3	0.249	0.320	0.336	0.359	0.413	0.356	0.353
Baca	3	0.246	0.370	0.416	0.460	0.584	0.467	0.461
Bill Brown	3	0.249	0.337	0.374	0.426	0.574	0.522	0.533
Bond CL	3	0.194	0.211	0.230	0.259	0.298	0.253	0.266
CO940610	3	0.236	0.360	0.391	0.457	0.573	0.493	0.517
Danby	3	0.233	0.307	0.349	0.362	0.435	0.406	0.377

Goodstreak	3	0.235	0.285	0.292	0.322	0.363	0.292	0.304
Hatcher	3	0.207	0.239	0.277	0.315	0.347	0.307	0.315
Jagalene	3	0.235	0.335	0.345	0.372	0.418	0.368	0.354
Jagger	3	0.263	0.375	0.383	0.436	0.495	0.408	0.385
Keota	3	0.234	0.282	0.322	0.360	0.399	0.355	0.337
NuDakota	3	0.214	0.263	0.266	0.282	0.338	0.290	0.303
Platte	3	0.242	0.322	0.360	0.351	0.426	0.376	0.361
Prairie Red	3	0.227	0.299	0.301	0.344	0.373	0.300	0.313
Prowers 99	3	0.212	0.263	0.281	0.320	0.369	0.311	0.315
Ripper	3	0.268	0.363	0.407	0.439	0.564	0.468	0.427
RonL	3	0.236	0.285	0.289	0.291	0.332	0.301	0.279
Sandy	3	0.220	0.266	0.330	0.396	0.457	0.412	0.404
Snowmass	3	0.285	0.388	0.399	0.468	0.569	0.461	0.443
TAM 112	3	0.243	0.337	0.399	0.457	0.593	0.493	0.485
Yuma	3	0.218	0.326	0.366	0.415	0.471	0.412	0.432

Table A.7 Continued

Genotypes	Rep	NDVI date8	NDVI date9	NDVI date10	NDVI date11	NDVI date12	NDVI date13	NDVI date14
Above	1	0.229	0.269	0.291	0.311	0.412	0.440	0.204
Ankor	1	0.144	0.150	0.155	0.172	0.206	0.290	0.169
Arlin	1	0.169	0.186	0.179	0.224	0.219	0.309	0.185
Avalanche	1	0.166	0.182	0.186	0.226	0.279	0.382	0.183
Baca	1	0.195	0.219	0.241	0.285	0.312	0.343	0.171
Bill Brown	1	0.182	0.207	0.212	0.257	0.275	0.313	0.157
Bond CL	1	0.208	0.224	0.232	0.280	0.317	0.355	0.174
CO940610	1	0.208	0.234	0.240	0.303	0.359	0.462	0.236
Danby	1	0.245	0.287	0.314	0.343	0.496	0.515	0.258
Goodstreak	1	0.169	0.178	0.204	0.272	0.316	0.397	0.229
Hatcher	1	0.251	0.257	0.278	0.342	0.424	0.465	0.207
Jagalene	1	0.234	0.247	0.267	0.322	0.356	0.391	0.172
Jagger	1	0.150	0.162	0.161	0.186	0.206	0.274	0.168
Keota	1	0.180	0.184	0.199	0.252	0.271	0.386	0.190
NuDakota	1	0.236	0.263	0.269	0.352	0.377	0.462	0.225
Platte	1	0.202	0.218	0.225	0.273	0.295	0.327	0.153
Prairie Red	1	0.198	0.235	0.230	0.285	0.301	0.320	0.156
Prowers 99	1	0.186	0.205	0.203	0.239	0.267	0.350	0.168
Ripper	1	0.214	0.240	0.259	0.282	0.334	0.399	0.220
RonL	1	0.190	0.218	0.216	0.238	0.270	0.364	0.185
Sandy	1	0.219	0.256	0.253	0.338	0.360	0.447	0.190
Snowmass	1	0.194	0.199	0.210	0.268	0.360	0.512	0.211
TAM 112	1	0.236	0.282	0.315	0.352	0.412	0.417	0.234
Yuma	1	0.179	0.192	0.213	0.259	0.306	0.364	0.174
Above	2	0.494	0.544	0.555	0.593	0.578	0.536	0.207
Ankor	2	0.411	0.441	0.448	0.539	0.562	0.594	0.241

Arlin	2	0.384	0.394	0.412	0.430	0.512	0.518	0.215
Avalanche	2	0.450	0.494	0.524	0.520	0.596	0.560	0.206
Baca	2	0.413	0.443	0.448	0.613	0.600	0.609	0.275
Bill Brown	2	0.415	0.414	0.433	0.479	0.531	0.602	0.261
Bond CL	2	0.474	0.544	0.510	0.572	0.545	0.490	0.186
CO940610	2	0.485	0.550	0.555	0.578	0.631	0.585	0.250
Danby	2	0.437	0.505	0.517	0.551	0.640	0.585	0.260
Goodstreak	2	0.340	0.382	0.407	0.512	0.560	0.592	0.279
Hatcher	2	0.444	0.476	0.494	0.587	0.586	0.579	0.269
Jagalene	2	0.349	0.402	0.421	0.450	0.555	0.555	0.240
Jagger	2	0.364	0.430	0.433	0.486	0.509	0.493	0.208
Keota	2	0.376	0.422	0.434	0.481	0.524	0.544	0.198
NuDakota	2	0.381	0.433	0.441	0.513	0.544	0.556	0.219
Platte	2	0.388	0.410	0.452	0.531	0.556	0.563	0.217
Prairie Red	2	0.387	0.440	0.416	0.458	0.474	0.500	0.226
Prowers 99	2	0.262	0.278	0.292	0.306	0.422	0.463	0.223
Ripper	2	0.392	0.481	0.452	0.488	0.523	0.454	0.184
RonL	2	0.301	0.345	0.339	0.344	0.419	0.513	0.225
Sandy	2	0.376	0.423	0.447	0.516	0.537	0.566	0.227
Snowmass	2	0.304	0.340	0.340	0.400	0.468	0.503	0.208
TAM 112	2	0.328	0.376	0.382	0.419	0.447	0.492	0.245
Yuma	2	0.434	0.494	0.478	0.496	0.558	0.516	0.207
Above	3	0.566	0.590	0.591	0.594	0.625	0.612	0.219
Ankor	3	0.364	0.466	0.467	0.469	0.582	0.601	0.264
Arlin	3	0.515	0.571	0.574	0.597	0.571	0.549	0.206
Avalanche	3	0.383	0.401	0.423	0.496	0.531	0.556	0.210
Baca	3	0.484	0.508	0.528	0.597	0.647	0.624	0.265
Bill Brown	3	0.602	0.614	0.664	0.641	0.681	0.679	0.256
Bond CL	3	0.297	0.313	0.327	0.380	0.462	0.536	0.252
CO940610	3	0.552	0.622	0.656	0.647	0.641	0.628	0.226

Danby	3	0.427	0.481	0.501	0.545	0.619	0.613	0.264
Goodstreak	3	0.334	0.330	0.341	0.420	0.533	0.609	0.314
Hatcher	3	0.358	0.426	0.441	0.522	0.596	0.545	0.299
Jagalene	3	0.328	0.373	0.367	0.410	0.482	0.585	0.243
Jagger	3	0.419	0.461	0.470	0.538	0.605	0.537	0.217
Keota	3	0.364	0.411	0.449	0.466	0.545	0.633	0.293
NuDakota	3	0.327	0.354	0.373	0.426	0.509	0.556	0.260
Platte	3	0.392	0.460	0.472	0.490	0.570	0.604	0.229
Prairie Red	3	0.349	0.396	0.395	0.434	0.483	0.474	0.218
Prowers 99	3	0.335	0.346	0.367	0.432	0.565	0.638	0.323
Ripper	3	0.508	0.566	0.580	0.580	0.626	0.577	0.230
RonL	3	0.295	0.325	0.348	0.402	0.409	0.427	0.251
Sandy	3	0.424	0.416	0.457	0.520	0.630	0.630	0.316
Snowmass	3	0.474	0.536	0.561	0.657	0.610	0.580	0.210
TAM 112	3	0.535	0.618	0.628	0.587	0.626	0.588	0.287
Yuma	3	0.463	0.504	0.481	0.527	0.598	0.561	0.230

Table A.8 Mean NDVI data for site year II under Irrigated conditions.

Genotypes	Rep	NDVI date1	NDVI date2	NDVI date3	NDVI date4	NDVI date5	NDVI date6	NDVI date7
Above	1	0.205	0.282	0.413	0.472	0.643	0.598	0.673
Ankor	1	0.164	0.217	0.289	0.360	0.528	0.457	0.567
Arlin	1	0.178	0.241	0.347	0.416	0.595	0.580	0.651
Avalanche	1	0.215	0.300	0.440	0.501	0.688	0.646	0.744
Baca	1	0.233	0.299	0.470	0.580	0.768	0.733	0.762
Bill Brown	1	0.200	0.260	0.342	0.456	0.659	0.583	0.690
Bond CL	1	0.177	0.252	0.337	0.440	0.629	0.547	0.673
CO940610	1	0.211	0.285	0.395	0.500	0.674	0.637	0.706
Danby	1	0.186	0.254	0.366	0.481	0.654	0.580	0.691
Goodstreak	1	0.198	0.265	0.358	0.441	0.652	0.608	0.655
Hatcher	1	0.161	0.212	0.289	0.381	0.574	0.515	0.650
Jagalene	1	0.201	0.286	0.416	0.521	0.672	0.612	0.712
Jagger	1	0.200	0.255	0.370	0.398	0.536	0.496	0.568
Keota	1	0.215	0.291	0.430	0.518	0.693	0.675	0.702
NuDakota	1	0.215	0.303	0.429	0.540	0.747	0.704	0.721
Platte	1	0.195	0.251	0.355	0.488	0.650	0.514	0.592
Prairie Red	1	0.188	0.263	0.356	0.401	0.581	0.552	0.639
Prowers 99	1	0.197	0.254	0.405	0.476	0.618	0.554	0.666
Ripper	1	0.237	0.365	0.508	0.603	0.781	0.743	0.778
RonL	1	0.221	0.270	0.466	0.501	0.683	0.640	0.709
Sandy	1	0.213	0.288	0.432	0.545	0.746	0.671	0.772
Snowmass	1	0.207	0.314	0.416	0.573	0.727	0.669	0.738
TAM 112	1	0.261	0.370	0.547	0.667	0.814	0.797	0.805
Yuma	1	0.192	0.271	0.391	0.547	0.722	0.695	0.768
Above	2	0.235	0.334	0.488	0.622	0.776	0.725	0.731
Ankor	2	0.166	0.198	0.272	0.310	0.462	0.380	0.464

Arlin	2	0.190	0.222	0.288	0.376	0.514	0.440	0.488
Avalanche	2	0.200	0.242	0.297	0.343	0.412	0.361	0.438
Baca	2	0.218	0.285	0.366	0.423	0.599	0.534	0.626
Bill Brown	2	0.211	0.291	0.381	0.369	0.578	0.499	0.592
Bond CL	2	0.187	0.244	0.318	0.377	0.516	0.459	0.560
CO940610	2	0.181	0.228	0.292	0.341	0.474	0.384	0.485
Danby	2	0.179	0.211	0.289	0.344	0.464	0.372	0.468
Goodstreak	2	0.195	0.249	0.314	0.389	0.561	0.444	0.571
Hatcher	2	0.186	0.242	0.336	0.443	0.630	0.578	0.674
Jagalene	2	0.179	0.222	0.295	0.371	0.511	0.435	0.546
Jagger	2	0.180	0.216	0.287	0.339	0.467	0.351	0.431
Keota	2	0.187	0.228	0.321	0.414	0.570	0.487	0.618
NuDakota	2	0.204	0.268	0.334	0.432	0.623	0.519	0.596
Platte	2	0.179	0.247	0.324	0.372	0.528	0.455	0.551
Prairie Red	2	0.186	0.259	0.349	0.411	0.573	0.576	0.653
Prowers 99	2	0.201	0.265	0.355	0.390	0.562	0.435	0.551
Ripper	2	0.221	0.325	0.431	0.497	0.685	0.607	0.659
RonL	2	0.213	0.295	0.372	0.426	0.605	0.511	0.624
Sandy	2	0.174	0.230	0.312	0.418	0.620	0.507	0.638
Snowmass	2	0.187	0.259	0.386	0.449	0.624	0.598	0.628
TAM 112	2	0.196	0.259	0.339	0.387	0.523	0.470	0.501
Yuma	2	0.186	0.237	0.304	0.384	0.551	0.496	0.601
Above	3	0.222	0.307	0.402	0.548	0.747	0.689	0.694
Ankor	3	0.242	0.321	0.521	0.623	0.799	0.777	0.785
Arlin	3	0.202	0.299	0.372	0.503	0.662	0.628	0.631
Avalanche	3	0.291	0.445	0.588	0.715	0.844	0.805	0.825
Baca	3	0.258	0.406	0.563	0.738	0.836	0.824	0.784
Bill Brown	3	0.206	0.320	0.432	0.506	0.714	0.682	0.724
Bond CL	3	0.203	0.285	0.382	0.484	0.724	0.664	0.689
CO940610	3	0.233	0.320	0.443	0.541	0.759	0.709	0.760

Danby	3	0.216	0.327	0.460	0.521	0.743	0.719	0.744
Goodstreak	3	0.212	0.279	0.363	0.428	0.655	0.610	0.641
Hatcher	3	0.191	0.280	0.396	0.505	0.692	0.633	0.755
Jagalene	3	0.246	0.363	0.496	0.608	0.738	0.711	0.736
Jagger	3	0.226	0.309	0.424	0.471	0.703	0.726	0.657
Keota	3	0.226	0.316	0.464	0.587	0.731	0.700	0.736
NuDakota	3	0.226	0.292	0.409	0.488	0.710	0.684	0.659
Platte	3	0.205	0.301	0.386	0.547	0.697	0.601	0.697
Prairie Red	3	0.225	0.331	0.480	0.614	0.759	0.725	0.743
Prowers 99	3	0.253	0.367	0.483	0.537	0.697	0.674	0.704
Ripper	3	0.252	0.395	0.518	0.615	0.788	0.729	0.767
RonL	3	0.241	0.317	0.476	0.525	0.694	0.670	0.676
Sandy	3	0.223	0.304	0.423	0.520	0.720	0.697	0.695
Snowmass	3	0.228	0.319	0.455	0.594	0.770	0.735	0.743
TAM 112	3	0.239	0.354	0.491	0.696	0.828	0.796	0.799
Yuma	3	0.209	0.336	0.515	0.636	0.795	0.787	0.804

Table A.8 Continued

Genotypes	Rep	NDVI date8	NDVI date9	NDVI date10	NDVI date11	NDVI date12	NDVI date13	NDVI date14
Above	1	0.782	0.812	0.840	0.834	0.789	0.754	0.503
Ankor	1	0.698	0.762	0.798	0.802	0.788	0.795	0.681
Arlin	1	0.797	0.816	0.843	0.809	0.757	0.699	0.455
Avalanche	1	0.809	0.813	0.844	0.829	0.796	0.769	0.568
Baca	1	0.819	0.832	0.837	0.827	0.780	0.673	0.478
Bill Brown	1	0.776	0.815	0.829	0.823	0.786	0.779	0.614
Bond CL	1	0.814	0.814	0.862	0.835	0.787	0.773	0.614
CO940610	1	0.807	0.757	0.827	0.779	0.777	0.729	0.556
Danby	1	0.803	0.816	0.835	0.844	0.780	0.800	0.677
Goodstreak	1	0.788	0.824	0.851	0.820	0.813	0.787	0.645
Hatcher	1	0.806	0.818	0.825	0.841	0.807	0.801	0.722
Jagalene	1	0.800	0.816	0.838	0.799	0.784	0.805	0.658
Jagger	1	0.715	0.740	0.786	0.764	0.776	0.790	0.647
Keota	1	0.793	0.765	0.835	0.781	0.785	0.745	0.597
NuDakota	1	0.796	0.818	0.850	0.792	0.801	0.786	0.609
Platte	1	0.729	0.760	0.785	0.769	0.762	0.779	0.615
Prairie Red	1	0.746	0.783	0.806	0.785	0.786	0.772	0.669
Prowers 99	1	0.805	0.843	0.863	0.844	0.797	0.741	0.486
Ripper	1	0.815	0.824	0.843	0.818	0.772	0.702	0.429
RonL	1	0.813	0.830	0.859	0.818	0.789	0.779	0.658
Sandy	1	0.850	0.851	0.874	0.862	0.798	0.734	0.522
Snowmass	1	0.830	0.837	0.858	0.830	0.762	0.655	0.508
TAM 112	1	0.849	0.834	0.852	0.803	0.780	0.765	0.593
Yuma	1	0.846	0.843	0.866	0.843	0.802	0.779	0.568
Above	2	0.811	0.816	0.830	0.806	0.787	0.760	0.528
Ankor	2	0.650	0.738	0.753	0.769	0.799	0.795	0.704
Arlin	2	0.676	0.687	0.686	0.700	0.736	0.737	0.610

Avalanche	2	0.581	0.621	0.621	0.690	0.750	0.751	0.591
Baca	2	0.779	0.790	0.827	0.815	0.808	0.798	0.700
Bill Brown	2	0.755	0.783	0.836	0.828	0.804	0.835	0.742
Bond CL	2	0.728	0.743	0.774	0.786	0.759	0.764	0.692
CO940610	2	0.670	0.709	0.736	0.747	0.770	0.751	0.689
Danby	2	0.691	0.776	0.810	0.820	0.813	0.791	0.735
Goodstreak	2	0.717	0.765	0.781	0.815	0.803	0.784	0.598
Hatcher	2	0.811	0.835	0.846	0.816	0.787	0.787	0.704
Jagalene	2	0.726	0.757	0.782	0.803	0.790	0.786	0.725
Jagger	2	0.585	0.663	0.687	0.711	0.769	0.778	0.711
Keota	2	0.723	0.743	0.766	0.743	0.768	0.792	0.658
NuDakota	2	0.726	0.784	0.804	0.801	0.794	0.783	0.674
Platte	2	0.708	0.744	0.784	0.808	0.803	0.795	0.684
Prairie Red	2	0.752	0.769	0.782	0.769	0.786	0.788	0.675
Prowers 99	2	0.688	0.772	0.810	0.831	0.799	0.817	0.739
Ripper	2	0.762	0.764	0.793	0.801	0.769	0.747	0.662
RonL	2	0.715	0.760	0.762	0.725	0.758	0.755	0.628
Sandy	2	0.796	0.800	0.841	0.810	0.817	0.825	0.698
Snowmass	2	0.785	0.813	0.818	0.805	0.777	0.761	0.630
TAM 112	2	0.711	0.727	0.762	0.780	0.761	0.768	0.704
Yuma	2	0.755	0.773	0.775	0.801	0.783	0.791	0.709
Above	3	0.830	0.824	0.858	0.839	0.794	0.774	0.624
Ankor	3	0.868	0.871	0.888	0.866	0.820	0.829	0.756
Arlin	3	0.768	0.781	0.816	0.770	0.749	0.750	0.699
Avalanche	3	0.859	0.827	0.845	0.838	0.798	0.775	0.587
Baca	3	0.893	0.882	0.857	0.868	0.828	0.824	0.732
Bill Brown	3	0.846	0.847	0.876	0.834	0.810	0.802	0.772
Bond CL	3	0.834	0.839	0.828	0.840	0.794	0.782	0.642
CO940610	3	0.833	0.846	0.828	0.828	0.789	0.772	0.620
Danby	3	0.864	0.874	0.864	0.864	0.829	0.826	0.766

Goodstreak	3	0.832	0.829	0.850	0.855	0.829	0.819	0.734
Hatcher	3	0.845	0.860	0.856	0.849	0.807	0.813	0.757
Jagalene	3	0.838	0.851	0.829	0.823	0.790	0.795	0.688
Jagger	3	0.835	0.849	0.844	0.850	0.821	0.827	0.751
Keota	3	0.816	0.824	0.818	0.824	0.804	0.779	0.708
NuDakota	3	0.811	0.827	0.826	0.839	0.812	0.811	0.675
Platte	3	0.811	0.830	0.839	0.846	0.827	0.810	0.753
Prairie Red	3	0.841	0.833	0.825	0.818	0.807	0.800	0.755
Prowers 99	3	0.827	0.854	0.863	0.856	0.819	0.828	0.705
Ripper	3	0.837	0.826	0.845	0.840	0.780	0.783	0.696
RonL	3	0.801	0.787	0.802	0.818	0.775	0.788	0.742
Sandy	3	0.833	0.802	0.837	0.845	0.811	0.828	0.741
Snowmass	3	0.854	0.855	0.870	0.838	0.783	0.755	0.632
TAM 112	3	0.876	0.849	0.868	0.821	0.793	0.790	0.731
Yuma	3	0.884	0.849	0.879	0.861	0.827	0.836	0.755

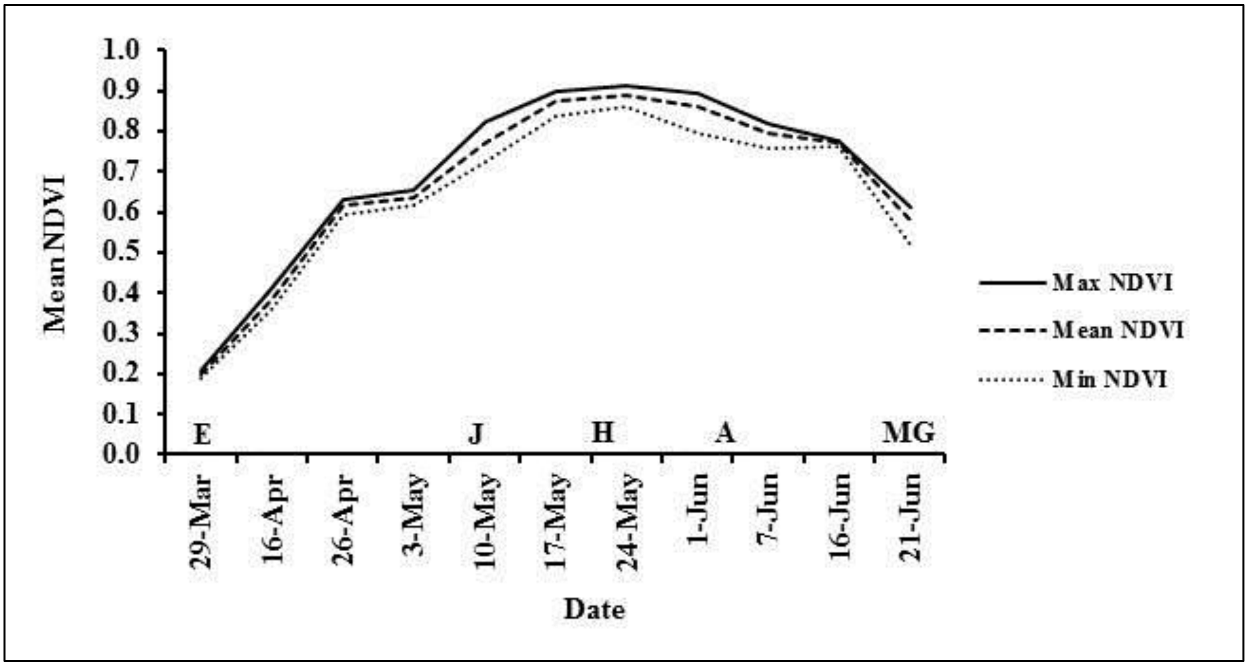

Figure A.1 Time-series of maximum, minimum and mean NDVI values for individual winter wheat (CO940610) genotype selected across the growing season under irrigated conditions for site I (11 dates for NDVI readings). Crop growth stages are indicated as E=early spring, J= jointing, H= heading, A= anthesis, and MG= mid-grain filling.

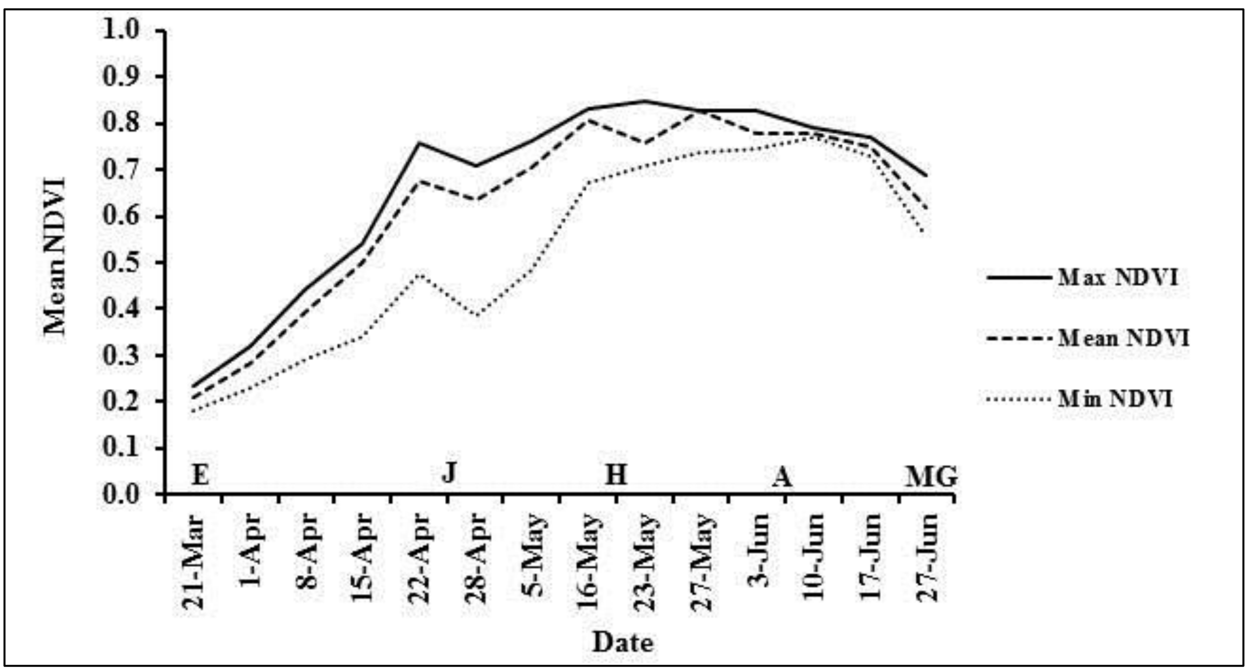

Figure A.2 Time-series of maximum, minimum and mean NDVI values for individual winter wheat (CO940610) genotype selected across the growing season under irrigated conditions for site II (14 dates for NDVI readings). Crop growth stages are indicated as E=early spring, J= jointing, H= heading, A= anthesis, and MG= mid-grain filling.

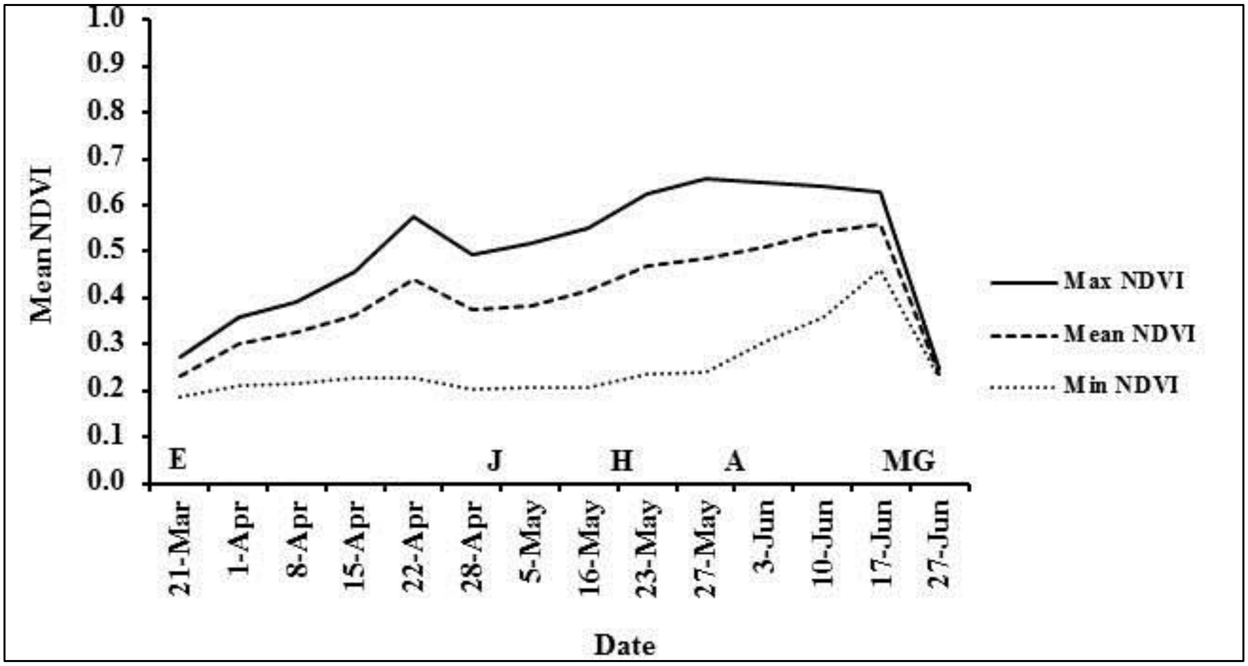

Figure A.3 Time-series of maximum, minimum and mean NDVI values for individual winter wheat (CO940610) genotype selected across the growing season under dryland conditions for site II (14 dates for NDVI readings). Crop growth stages are indicated as E=early spring, J= jointing, H= heading, A= anthesis, and MG= mid-grain filling.

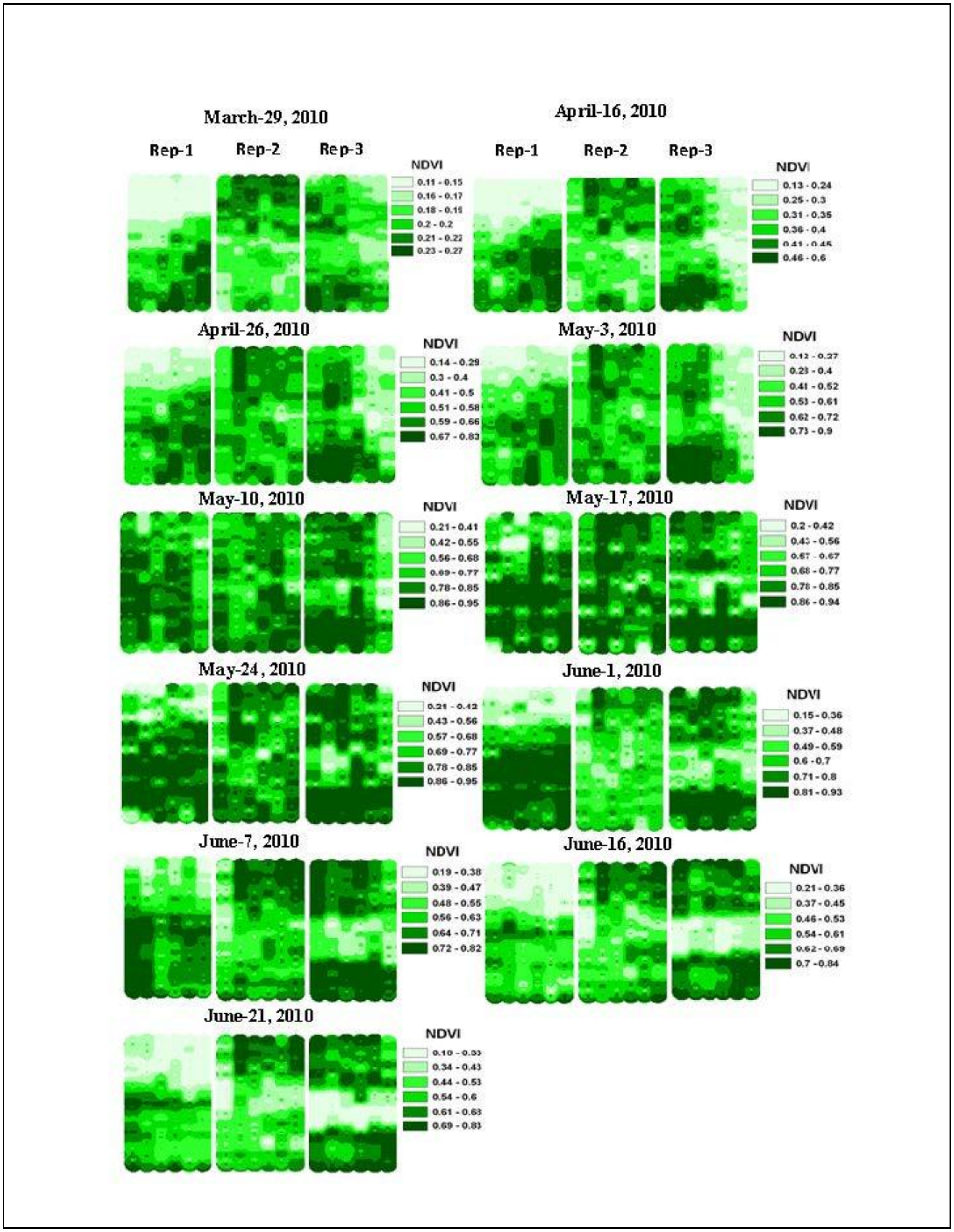

Figure A.4 Maps of spatial variability of NDVI values across 24 winter wheat genotypes collected under dryland conditions for 11 dates across site year I.

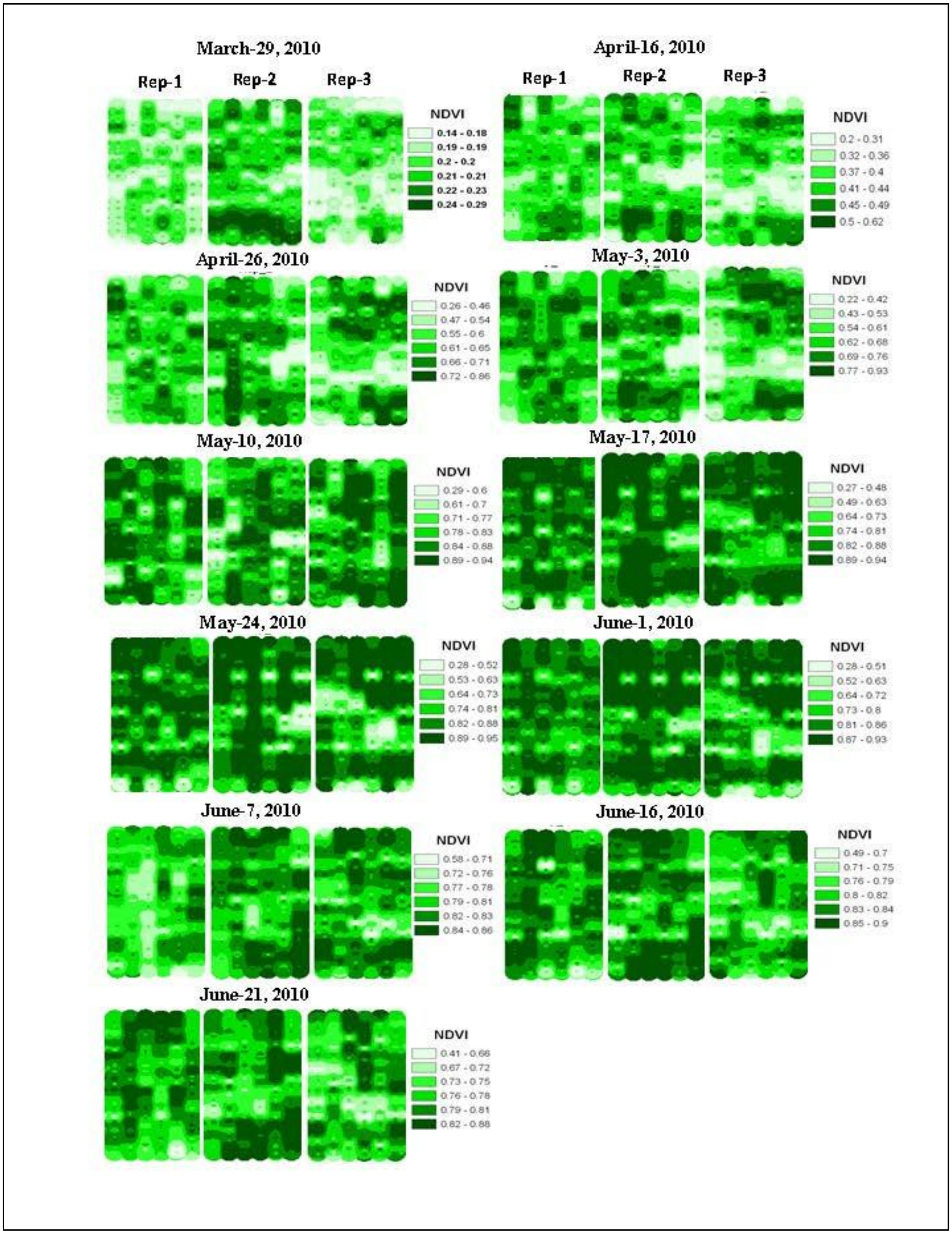

Figure A.5 Maps of spatial variability of NDVI values across 24 winter wheat genotypes collected under Irrigated conditions for 11 dates across site year I.

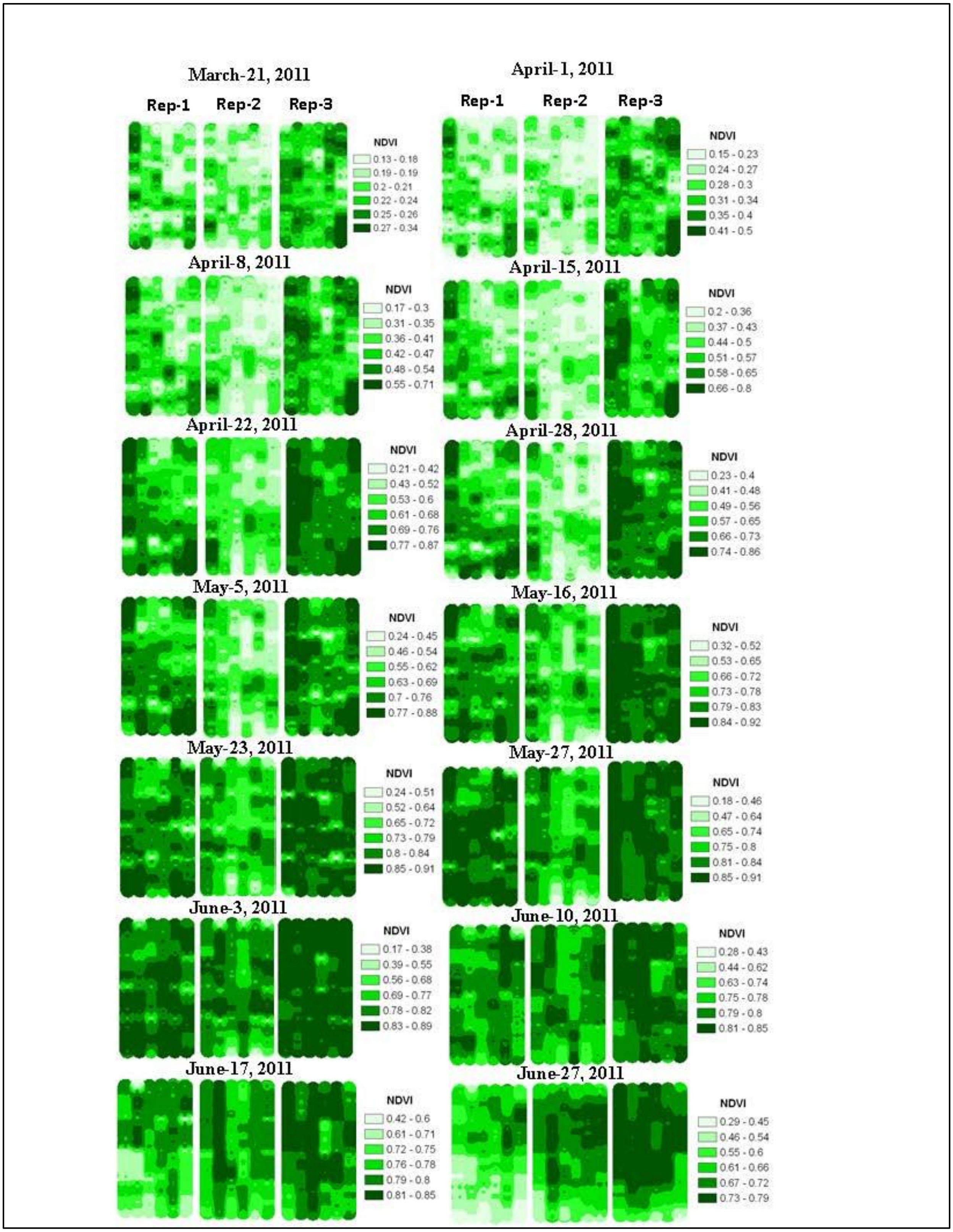

Figure A.6 Maps of spatial variability of NDVI values across 24 winter wheat genotypes collected under Irrigated conditions for 14 dates across site year II.

APPENDIX B

Data from chapter 2

Table B.1 Analysis of variance for nitrogen use efficiency as partial factor productivity (PFP) under dryland conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	317.8	158.91	0.7475	0.4792
Genotypes	23	5576.1	242.44	1.1404	0.3431
Residuals	46	9779	212.59		

Table B.2 Analysis of variance for nitrogen use efficiency as partial nitrogen balance (PNB) under dryland conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	0.2961	0.14807	1.564	0.2202
Genotypes	23	2.5829	0.1123	1.1862	0.3037
Residuals	46	4.3551	0.09468		

Table B.3 Analysis of variance for nitrogen use efficiency as partial factor productivity (PFP) under irrigated conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	175.1	87.539	0.6381	0.5329
Genotypes	23	2929.6	127.375	0.9284	0.5647
Residuals	46	6311	137.197		

Table B.4 Analysis of variance for nitrogen use efficiency as partial nitrogen balance (PNB) under irrigated conditions for site year I.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	0.03816	0.01908	0.28	0.757
Genotypes	23	1.14755	0.04989	0.7323	0.7881
Residuals	46	3.13418	0.06813		

Table B.5 Analysis of variance for nitrogen use efficiency as partial factor productivity (PFP) under dryland conditions for site year II

	Df	Sum Sq	Mean Sq	F value	Pr (>F) [1]
Rep	2	3433.4	1716.68	125.129	2.00E-16***
Genotypes	23	689.1	29.96	2.1839	0.01203*
Residuals	46	631.1	13.72		

Table B.6 Analysis of variance for nitrogen use efficiency as partial nitrogen balance (PNB) under dryland conditions for site year II.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	2.13284	1.06642	128.856	2.00E-16***
Genotypes	23	0.34206	0.01487	1.797	0.04517*
Residuals	46	0.3807	0.00828		

Table B.7 Analysis of variance for nitrogen use efficiency as partial factor productivity (PFP) under irrigated conditions for site year II.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	3807.6	1903.82	68.7891	1.50E-14***
Genotypes	23	2344.3	101.93	3.6829	8.29E-05***
Residuals	46	1273.1	27.68		

Table B.8 Analysis of variance for nitrogen use efficiency as partial nitrogen balance (PNB) under irrigated conditions for site year II.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Rep	2	1.1401	0.57005	41.4626	5.08E-11***
Genotypes	23	0.86482	0.0376	2.7349	0.001821**
Residuals	46	0.63243	0.01375		

[1] Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table B.9 Selected of soil properties for soil samples acquired at depths of 0-20 cm and 20-61 cm. Soil NO_3-N contents were determined on samples collected on March 22nd (at early spring) and August 19th of 2010 (after harvest) for site year I.

Sample number	Sampling location	Sampling depths (cm)	pH	O.M %	N at early spring Mg g^{-1}	N after harvest Mg g^{-1}	Sand	Silt	Clay	Soil texture
								%		
1	1A	0-20	8.0	1.2	24.0	9.0	68.8	15.6	15.6	Sandy Loam
2	1B	20-61	8.0	1.1	19.0	35.0	70.8	15.6	13.6	Sandy Loam
3	2A	0-20	8.1	1.2	25.0	9.0	68.8	21.6	9.6	Sandy Loam
4	2B	20-61	8.1	1.2	17.0	10.0	70.8	15.6	13.6	Sandy Loam
5	3A	0-20	8.1	1.2	38.0	7.0	66.8	19.6	13.6	Sandy Loam
6	3B	20-61	7.9	1.1	21.0	7.0	68.8	19.6	11.6	Sandy Loam
7	4A	0-20	8.0	1.3	32.0	14.0	70.8	17.6	11.6	Sandy Loam
8	4B	20-61	7.9	1.3	22.0	37.0	64.8	17.6	17.6	Sandy Loam
9	5A	0-20	8.0	1.1	22.0	9.0	66.8	17.6	15.6	Sandy Loam
10	5B	20-61	8.1	1.2	21.0	10.0	60.8	21.6	17.6	Sandy Loam
11	6A	0-20	8.0	1.2	34.0	8.0	72.8	15.6	11.6	Sandy Loam
12	6B	20-61	8.0	1.2	21.0	8.0	66.8	19.6	13.6	Sandy Loam
13	7A	0-20	8.1	1.2	26.0	5.0	66.8	19.6	13.6	Sandy Loam
14	7B	20-61	8.0	1.1	29.0	7.0	68.8	15.6	15.6	Sandy Loam
15	8A	0-20	8.0	1.2	31.0	9.0	70.8	15.6	13.6	Sandy Loam
16	8B	20-61	8.1	1.1	20.0	11.0	66.8	17.6	15.6	Sandy Loam
17	9A	0-20	8.0	1.2	37.0	7.0	70.8	13.6	15.6	Sandy Loam
18	9B	20-61	7.9	1.1	24.0	9.0	66.8	17.6	15.6	Sandy Loam
19	10A	0-20	8.1	1.1	30.0	6.0	66.8	15.6	17.6	Sandy Loam
20	10B	20-61	8.1	1.1	21.0	7.0	66.8	15.6	17.6	Sandy Loam
21	11A	0-20	7.9	1.1	23.0	6.0	66.8	15.6	17.6	Sandy Loam
22	11B	20-61	8.1	1.1	11.0	8.0	72.8	13.6	13.6	Sandy Loam
23	12A	0-20	8.0	1.1	23.0	8.0	66.8	15.6	17.6	Sandy Loam

24	12B	20-61	8.0	1.1	20.0	8.0	68.8	15.6	15.6	Sandy Loam
25	13A	0-20	8.1	1.0	31.0	6.0	68.8	13.6	17.6	Sandy Loam
26	13B	20-61	8.2	1.0	19.0	5.0	68.8	15.6	15.6	Sandy Loam
27	14A	0-20	8.0	1.0	42.0	7.0	68.8	13.6	17.6	Sandy Loam
28	14B	20-61	8.0	1.1	30.0	10.0	68.8	15.6	15.6	Sandy Loam
29	15A	0-20	8.0	1.0	47.0	8.0	64.8	17.6	17.6	Sandy Loam
30	15B	20-61	8.0	0.9	40.0	15.0	64.8	17.6	17.6	Sandy Loam

Table B.10 Selected of soil properties for soil samples acquired at depths of 0-20 cm and 20-61 cm. Soil NO_3-N contents were determined on samples collected November 8th 2010 (at early fall) and August 22nd 2011(after harvest) for site year II.

Sample number	Sampling location	Sampling depths (cm)	pH	O.M %	N at early fall Mg g^{-1}	N after harvest Mg g^{-1}	Sand %	Silt %	Clay %	Soil texture
1	1A	0-20	8.1	1.5	31.0	12.0	58.8	24.4	16.8	Sandy Loam
2	1B	20-61	8.1	1.3	26.0	8.0	60.8	20.4	18.8	Sandy Loam
3	2A	0-20	8.1	1.2	34.0	8.0	60.8	22.4	16.8	Sandy Loam
4	2B	20-61	8.2	1.1	20.0	5.0	58.8	16.4	24.8	Sandy Loam
5	3A	0-20	8.0	1.2	35.0	22.0	64.8	18.4	16.8	Sandy Loam
6	3B	20-61	8.3	1.0	22.0	22.0	62.8	16.4	20.8	Sandy Loam
7	4A	0-20	7.9	1.1	36.0	16.0	64.8	18.4	16.8	Sandy Loam
8	4B	20-61	8.2	0.9	19.0	12.0	64.8	16.4	18.8	Sandy Loam
9	5A	0-20	8.1	1.1	31.0	16.0	64.8	4.4	30.8	Sandy Loam
10	5B	20-61	8.1	0.8	23.0	7.0	62.8	12.4	24.8	Sandy Loam
11	6A	0-20	8.1	1.1	32.0	13.0	66.8	16.4	16.8	Sandy Loam
12	6B	20-61	8.3	0.9	16.0	8.0	58.8	22.4	18.8	Sandy Loam
13	7A	0-20	8.0	1.1	39.0	19.0	62.8	20.4	16.8	Sandy Loam
14	7B	20-61	8.4	0.9	16.0	8.0	62.8	16.4	20.8	Sandy Loam
15	8A	0-20	8.0	1.1	30.0	14.0	70.8	16.4	12.8	Sandy Loam
16	8B	20-61	8.1	1.0	18.0	9.0	66.8	16.4	16.8	Sandy Loam
17	9A	0-20	8.0	1.2	46.0	18.0	64.8	20.4	14.8	Sandy Loam
18	9B	20-61	8.1	1.0	20.0	11.0	62.8	18.4	18.8	Sandy Loam
19	10A	0-20	7.9	1.2	30.0	NA	62.8	8.4	28.8	Sandy Loam
20	10B	20-61	8.1	1.0	25.0	5.0	60.8	14.4	24.8	Sandy Loam
21	11A	0-20	7.8	1.3	49.0	17.0	61.2	23.6	15.2	Sandy Loam
22	11B	20-61	8.0	1.0	23.0	9.0	53.2	27.6	19.2	Sandy Loam
23	12A	0-20	7.8	1.0	35.0	18.0	69.2	15.6	15.2	Sandy Loam

24	12B	20-61	8.1	1.0	22.0	11.0	65.2	19.6	15.2	Sandy Loam
25	13A	0-20	7.9	1.2	45.0	9.0	63.2	19.6	17.2	Sandy Loam
26	13B	20-61	8.2	1.0	21.0	4.0	57.2	23.6	19.2	Sandy Loam
27	14A	0-20	8.0	1.3	43.0	15.0	69.2	13.6	17.2	Sandy Loam
28	14B	20-61	8.2	1.0	21.0	11.0	61.2	21.6	17.2	Sandy Loam
29	15A	0-20	7.8	1.3	54.0	19.0	69.2	7.6	23.2	Sandy Loam
30	15B	20-61	8.0	1.1	44.0	17.0	67.2	3.6	29.2	Sandy Loam

Table B.11 Mean nitrogen use efficiency and parameters related under dryland conditions for site year I.

Genotypes	PFP	PNB	UPE	UTE	BPE	GN/BW	Yield(kg ha^{-1})
Above	47.57	1.11	1.96	23.69	53.02	0.011	3996.17
Ankor	55.08	1.28	2.18	25.25	55.27	0.011	4626.95
Arlin	43.41	0.95	2.09	20.35	57.72	0.008	3646.41
Avalanche	63.25	1.43	2.68	24.88	52.53	0.010	5313.29
Baca	39.40	0.92	1.86	20.07	49.38	0.010	3309.46
Bill Brown	58.51	1.32	2.35	25.41	54.63	0.011	4914.94
Bond CL	34.54	0.85	1.71	20.18	49.09	0.010	2901.49
CO940610	56.69	1.37	2.42	23.29	47.41	0.012	4762.32
Danby	43.88	1.08	1.96	22.33	58.07	0.010	3686.19
Goodstreak	38.46	1.02	2.64	15.76	67.10	0.006	3230.63
Hatcher	46.06	1.10	1.84	25.04	54.90	0.011	3869.32
Jagalene	42.50	1.06	2.08	25.22	54.87	0.010	3569.99
Jagger	46.68	1.15	2.02	22.98	66.40	0.009	3920.86
Keota	31.41	0.76	1.67	18.36	62.56	0.009	2638.67
NuDakota	36.20	0.85	1.53	23.98	60.53	0.010	3040.50
Platte	35.57	0.94	1.93	18.06	58.28	0.009	2987.57
Prairie Red	51.06	1.20	1.84	27.11	64.50	0.011	4289.38
Prowers 99	53.54	1.28	2.21	23.94	49.93	0.012	4497.70
Ripper	65.03	1.55	2.45	26.49	53.46	0.012	5462.35
RonL	43.29	1.10	2.00	20.09	51.43	0.011	3636.47
Sandy	47.94	1.20	1.98	24.26	48.06	0.013	4026.80
Snowmass	54.04	1.24	2.18	24.38	61.59	0.009	4539.38
TAM 112	49.97	1.15	2.09	24.29	66.42	0.009	4197.16
Yuma	52.23	1.13	2.33	22.80	54.74	0.009	4387.52

Table B.12 Mean nitrogen use efficiency and parameters related under irrigated conditions for site year I.

Genotypes	PFP	PNB	UPE	UTE	BPE	GN/BW	Yield(kg ha^{-1})
Above	86.12	1.78	3.30	26.21	60.88	0.009	7234.36
Ankor	74.43	1.49	2.53	30.19	59.27	0.010	6252.39
Arlin	93.33	1.94	2.97	31.68	63.03	0.010	7839.97
Avalanche	83.30	1.70	2.95	28.41	62.70	0.009	6996.92
Baca	78.98	1.86	3.05	26.20	64.60	0.010	6634.25
Bill Brown	89.02	1.79	3.29	27.26	64.72	0.008	7477.86
Bond CL	84.97	1.70	2.86	29.76	55.81	0.011	7137.12
CO940610	90.78	1.86	3.68	25.02	53.15	0.010	7625.82
Danby	96.38	1.93	3.09	31.32	58.37	0.011	8096.07
Goodstreak	71.27	1.72	2.88	25.61	59.37	0.011	5986.30
Hatcher	82.51	1.66	2.70	30.34	64.94	0.010	6930.91
Jagalene	78.35	1.61	3.33	23.43	52.04	0.009	6581.20
Jagger	83.39	1.81	3.03	27.70	55.79	0.011	7004.93
Keota	93.70	1.85	3.20	29.56	59.18	0.010	7870.48
NuDakota	87.73	1.74	3.45	25.79	51.38	0.010	7369.14
Platte	83.46	1.81	3.05	27.43	51.27	0.012	7010.23
Prairie Red	87.45	1.76	2.99	29.99	58.70	0.010	7345.65
Prowers 99	81.68	1.86	3.12	26.22	54.45	0.011	6861.06
Ripper	83.54	1.69	2.97	28.73	54.58	0.011	7017.71
RonL	89.38	1.83	3.22	27.73	61.92	0.009	7507.98
Sandy	84.73	1.78	3.14	27.23	55.92	0.010	7117.70
Snowmass	92.21	1.92	3.46	27.19	61.20	0.009	7745.97
TAM 112	83.56	1.75	2.77	29.95	61.81	0.010	7018.97
Yuma	72.41	1.41	2.23	32.65	70.94	0.009	6082.66

Table B.13 Mean nitrogen use efficiency and parameters related under irrigated conditions for site year II.

Genotypes	PFP	PNB	UPE	UTE	BPE	GN/BW	Yield(kg ha^{-1})
Above	73.03	1.67	2.23	32.67	80.97	0.009	8179.61
Ankor	67.60	1.52	1.93	35.05	108.07	0.007	7571.55
Arlin	66.97	1.54	2.38	29.97	81.23	0.008	7500.78
Avalanche	66.90	1.55	1.91	34.78	97.42	0.008	7492.82
Baca	59.06	1.47	2.01	29.53	97.22	0.008	6615.20
Bill Brown	72.21	1.58	2.17	33.19	95.73	0.008	8087.50
Bond CL	72.72	1.55	2.07	35.27	104.33	0.008	8145.00
CO940610	69.02	1.63	1.94	35.57	100.49	0.008	7730.25
Danby	69.02	1.54	2.01	34.42	100.15	0.008	7730.11
Goodstreak	65.86	1.61	1.89	35.23	102.23	0.008	7376.22
Hatcher	72.66	1.58	2.15	33.79	91.36	0.008	8138.21
Jagalene	69.30	1.63	1.92	36.89	98.36	0.008	7761.75
Jagger	71.11	1.70	2.01	35.68	99.36	0.009	7964.49
Keota	73.35	1.64	2.02	36.35	99.62	0.008	8215.17
NuDakota	79.67	1.80	2.12	37.84	97.19	0.009	8923.03
Platte	68.43	1.66	1.97	35.42	90.00	0.010	7664.27
Prairie Red	74.07	1.70	2.12	35.01	99.05	0.008	8295.71
Prowers 99	60.55	1.48	2.10	28.85	92.61	0.008	6781.71
Ripper	82.24	1.89	2.30	36.02	92.03	0.009	9210.42
RonL	75.85	1.68	2.02	37.53	89.26	0.010	8495.73
Sandy	65.40	1.52	2.20	30.21	97.61	0.007	7324.57
Snowmass	67.30	1.49	2.11	32.05	96.41	0.007	7537.67
TAM 112	81.42	1.86	2.26	36.11	85.41	0.010	9118.57
Yuma	77.08	1.62	2.06	37.48	97.69	0.008	8633.02

Table B.14 Mean nitrogen use efficiency and parameters related under dryland conditions for site year II.

Genotypes	PFP	PNB	UPE	UTE	BPE	GN/BW	Yield(kg ha^{-1})
Above	32.84	0.81	1.00	32.72	92.66	0.009	3678.07
Ankor	32.70	0.81	1.02	31.65	86.14	0.009	3662.51
Arlin	29.54	0.78	1.03	28.63	92.09	0.008	3308.10
Avalanche	27.56	0.72	0.79	29.04	92.44	0.008	3087.22
Baca	29.36	0.78	1.03	28.31	95.81	0.008	3288.00
Bill Brown	34.99	0.84	1.13	30.53	95.17	0.008	3919.12
Bond CL	34.06	0.78	0.99	34.41	93.84	0.009	3814.84
CO940610	33.92	0.88	1.10	30.84	88.06	0.009	3799.37
Danby	36.06	0.90	1.14	31.82	98.17	0.008	4038.67
Goodstreak	30.77	0.80	0.98	31.41	104.70	0.008	3445.90
Hatcher	30.55	0.73	1.04	29.45	89.68	0.008	3421.91
Jagalene	30.51	0.82	1.04	29.16	94.72	0.008	3417.58
Jagger	26.96	0.74	0.92	28.70	97.94	0.008	3019.93
Keota	29.97	0.75	0.90	32.97	108.93	0.008	3356.31
NuDakota	34.93	0.86	1.07	32.67	82.80	0.010	3911.74
Platte	29.26	0.82	1.03	28.32	96.89	0.008	3277.32
Prairie Red	27.93	0.71	0.80	30.73	106.38	0.008	3127.76
Prowers 99	25.79	0.65	0.74	29.23	108.54	0.007	2887.96
Ripper	31.47	0.82	1.04	30.65	104.29	0.008	3524.57
RonL	27.32	0.68	0.88	31.74	104.76	0.008	3059.81
Sandy	32.15	0.80	1.02	31.37	97.60	0.008	3601.12
Snowmass	30.51	0.73	0.94	32.24	108.13	0.007	3417.19
TAM 112	38.09	0.95	1.19	32.06	90.37	0.009	4265.65
Yuma	34.34	0.83	1.05	32.17	89.11	0.009	3846.39