PERFORMANCE OF WINTER WHEAT FOR GRAIN YIELD AND NITROGEN USE EFFICIENCY USING CANOPY REFLECTANCE INDICES

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CHAPTER I

INTRODUCTION

Visual selection is a common practice in wheat breeding programs. In fact, it is the best tool for selecting genotypes with the desirable traits from segregating populations. However, there are always subjective differences among breeders depending on theoretical knowledge, practical experience, and knowledge of the genetic background of the populations. Because of these differences, breeders need a tool that will increase the probability of selecting improved wheat genotypes for important agronomic traits such as grain yield, biomass, nitrogen use efficiency, etc. Hence, non-destructive canopy reflectance measurements have been proposed as an additional tool for selection of wheat genotypes prior to their entry into replicated multi-location trials (F_4-F_6). Normalized-difference vegetative index (NDVI), in-season estimated yield (INSEY), and estimated yield (EY) are the canopy reflectance measurements utilized in this experiment. The objectives were to determine the association of NDVI, INSEY, and EY with important agronomic traits such as grain yield, biomass, and nitrogen use efficiency, and to determine their value as selection criteria for identifying potentially superior wheat genotypes.

CHAPTER II

LITERATURE REVIEW

Canopy Reflectance Measurements (NDVI, INSEY, and EY)

Three types of canopy reflectance indices are considered in this research: normalized difference vegetative index (NDVI), in-season estimated yield (INSEY), and estimated yield (EY). These are defined as follows: NDVI $=[(NIR_{ref}/NIR_{inc}) - (RED_{ref}/RED_{inc})] / [(NIR_{ref}/NIR_{inc}) + (RED_{ref}/RED_{inc})]$, where NIR_{ref} and RED_{ref} are the magnitude of reflected light (or incident light for NIR_{inc} and RED_{inc}) in the near-infrared (780 ± 6nm) or in the red (670 ± 6nm) regions, respectively. INSEY is calculated from a single NDVI measurement between Feeke's growth stages 4 and 6, divided by the number of days from planting to the NDVI reading. Estimated yield is calculated as EY = $(NDVI_{T1} + NDVI_{T2})/GDD$, where subscripts T_1 and T_2 represent first and second NDVI readings at different physiological stages. GDD is cumulative growing degree days between T_1 and T_2, defined as GDD = (Temp-max + Temp-min)/2 - 4.44, where Temp-max and Temp-min are daily amaximum and minimum air temperatures (^{o}C) between the two NDVI readings (Stone et al., 1996a; Stone et al.,1996b; Raun et al., 2001).

NDVI is a widely used index for predicting photosynthetic area of the crop canopy. It has been used to estimate indirectly photosynthetic capacity and net primary productivity (Carlson et al., 1997; Field 1994; Aparicio et al., 2000; Wanjura and Hatfiled, 1987).

Reflectance measurements of chlorophyll A content offers the possibility of rapidly estimating crop N status and, therefore, crop productivity. Since leaf chlorophyll A is mainly determined by nitrogen availability, it is possible to monitor the nitrogen status of a large crop area using spectral indices, such as NDVI (Filella et al., 1995). NDVI is positively correlated with leaf area index, green area index, and the fraction of photosynthetic active radiation absorbed by the canopy in cereal crops (Bellairs et al., 1996; Fernandez et al., 1994; Field et al., 1994). However, Carlson et al. (1997) cautioned that NDVI increases linearly with increasing leaf area index up to a certain level only, beyond which its sensitivity to leaf area index becomes weaker. In winter wheat, NDVI is highly correlated with early-season plant N uptake and biomass at Feeke's growth stages 4 to 8 (Sembiring et al., 2000).

It has been reported that NDVI has the ability to predict early-season plant N uptake, and is positively correlated with grain yield. Estimated yield (EY) also is a reliable predictor of wheat biomass and grain yield, although its coefficient of determination is lower than INSEY. Biomass and grain yield may be predicted better with INSEY than with EY, with only one NDVI reading required for INSEY (Raun et al., 2001; Lukina et al., 2001). As EY and INSEY are derived from NDVI, both may share some redundancy with NDVI to some extent. Recent work by Lukina et al. (2001) also showed the possibility of predicting actual grain yield, early-season, N uptake, and in-season N top-dress requirements from NDVI and INSEY, but their study did not attempt to separate genetic versus environmental factors. No reports were found that demonstrated the possibility of differentiating genetic differences in grain yield, biomass, and other important traits for a range of genotypes using sensor readings.

N-use efficiency and its components

According to De Datta (1989), high N-use efficiency implies high grain production with the least fertilizer N input. It is defined by Moll et al. (1981) as grain production per unit of available N in the soil. Conventionally, N-use efficiency can be calculated using the formula, Gw/Ns, where Gw is grain weight (kg ha^{-1}) and Ns is total soil N supply (kg ha^{-1}). Nitrogen-use efficiency of different genotypes can be partitioned into components representing N-uptake and N-utilization efficiency. Each component can relate differently to yield and grain N differences between genotypes (Paponov et al., 1996). N-uptake efficiency is defined as Nt/Ns, and N-utilization efficiency is defined as Gw/Nt, where Nt is total amount of plant N (Moll et al. 1981; Paponov et al., 1996). The N-utilization efficiency can be defined as (B/Nt)(Gw/B), where B represents biomass (kg ha^{-1}), B/Nt is assimilation efficiency, i.e., efficiency of biomass formation per unit N taken up, and Gw/B is harvest index (HI). Determination of N-use efficiency and its components requires tedious plant and soil sample collection. Using canopy reflectance measurements, N uptake by wheat at early growth stages can be estimated (Lukina et al., 2001; Raun et al., 2001). NDVI and other NDVI-derived indices may be helpful in assessing N-use efficiency of the wheat crop by providing N status information at early growth stages. Thus, indirect selection of wheat lines for N-use efficiency may be possible.

Genetic variation in nitrogen use efficiency

Genetic variation exists for N-use efficiency in winter wheat (Kanampiu et al., 1997, van Sanford et al., 1986). N-uptake efficiency may account for most of the genetic variation in N-use efficiency for yield (NUEY) and for protein (NUEP) (van Sanford et al., 1986; May et al.,1991). Under non-limiting N conditions, a strong association exists between N uptake and either grain yield or protein per unit area (van Sanford et al., 1986). Selection for wheat yield is usually conducted under high N fertilizer input to avoid variability in soil fertility. Selection conducted under high fertilizer N may, however, mask differences among genotypes in accumulating and utilizing N efficiently to produce grain (Kamprath et al., 1982). Genotypes efficient in N uptake might be favored when N is abundant, but little or no selection pressure is applied for genotypes with greater capacity to utilize accumulated N (Moll et al., 1981). Hence, we need to understand genetic variation for converting N into grain production.

Consideration of growth stage is important to successfully select improved genotypes based on N utilization, because differences occur among cultivars in time of N assimilation in regard to pre- and post-anthesis periods (Cox et al, 1985a). A significant and consistent correlation was not repeated between pre-anthesis N assimilation and grain yield or grain protein content (Cox et al., 1985b).Broad-sense heritability was moderate for total N assimilation (Cox et al., 1985a). The total N assimilated in aboveground parts of the wheat plant is under reasonably strong genetic control (Cox et al., 1985b).

The two main objectives for this study were to test for the presence of genetic variation for grain yield, biomass, nitrogen use efficiency, nitrogen utilization efficiency, in-season estimated yield, estimated yield, and normalized difference vegetative index (hereafter referred as yield biomass, NUE, NUTE, INSEY, EY, and NDVI, respectively) and to determine the association of canopy reflectance measurements (EY, INSEY, and NDVI), with yield, biomass, NUE and NUTE. Other agronomic traits such as grain nitrogen (GN), straw nitrogen (SN), and total nitrogen (TN) were considered in the analysis.

CHAPTER III

MATERIALS AND METHODS

Experiment I

To examine the association of agronomic traits of wheat (yield, biomass, NUE, NUTE) with EY, INSEY, and NDVI, 20 early-generation breeding lines were selected from the 1999 OSU wheat breeding observation nursery (Appendix A). These lines were chosen to represent three phenotypic groups based on EY (high, medium, and low) measured at Stillwater, OK. Measurements recorded at Lahoma, Ok were not used to define phenotypic groups due to the absence of sufficient variability for EY (Figure 1). These lines were tested for their performance in agronomic and canopy reflectance measurements in 2000 at Stillwater and Lahoma, along with five check cultivars. A randomized complete block design with four replications was used with plots of 1.22 m wide by 3.05 m long. All plots received 90 kg ha^{-1} N in the form of ammonium nitrate.

Experiment II

Twenty commercially important winter wheat cultivars were used in this experiment (Appendix B) based on the following criteria: (i) long-term genetic advances in yield potential, (ii) genetic advances in grain protein content, (iii) most recent advances in yield potential of hard red winter (HRW) and hard white winter (HWW) wheat cultivars and lines, and (iv) genetic variation in plant stature.

To avoid bias from soil factors unrelated to N fertility, several of cultivars possessed soil-borne mosaic virus resistance. Cultivars were tested under sub-optimal and optimal nitrogen levels (0 and 90 kg ha^{-1} nitrogen, respectively), applied in the form of ammonium nitrate. Phosphorus was applied according to soil-test recommendations. All fertilizer treatments were applied prior to planting in one application. The experiment was arranged in split-plot design with four replications using fertilizer treatments as the main plot and cultivars as the sub-plot treatment at two locations (Efaw and Hennessey, OK). Each main plot had 20 sub-plots. A single sub-plot was 1.22 m wide by 4.28 m long, with five rows spaced at 0.24 m apart.

Canopy Reflectance Measurements (Experiments I and II)

Canopy reflectance readings were taken using a locally designed hand-held sensor, which includes two upward-directed photodiodes that receive incident light through cosine-corrected Teflon® windows fitted with red (RED) (671±6nm) and near-infrared (NIR) (780±6nm) interference filters. Since the genotypes were expected to vary in phenological pattern, the sensor readings were taken when the majority of genotypes were at the desired growth stage e.g., Feeke's 5 according to Large (1954).

Two experienced graduate students from the Oklahoma State University (OSU) soil fertility research program were involved in collecting the reflectance data from the field. Three spectral readings were collected from each plot and each location between Feeke's growth stages 5 to 9 (Appendix C). Canopy reflectance measurements were collected at different times and under different crop management conditions at Stillwater and Lahoma in 1999. In Stillwater, the wheat was clipped to simulate cattle grazing before sensor readings. At Lahoma, no clipping was done either before or after the sensor readings. NDVI, EY, and INSEY were calculated using the equations mentioned in the literature review. Different combinations of these NDVI readings were considered for the analysis.

Agronomic data (Experiments I and II)

Agronomic measurements taken included grain yield, biomass, plant height, heading date, and maturity date. Diseases such as barley yellow dwarf virus (BYDV) and leaf rust (*Puccinia triticina*) were noted as they might have had negative effects on yield and confounded the spectral readings. At maturity, the three middle rows were harvested with a binder at Stillwater and Efaw for Experiments I and II, and all 5 rows were machine-combined at Hennessy and Lahoma. Biomass was determined at Stillwater and Efaw from the harvested bundle and from a 1m length of row at Lahoma. At Hennessey, biomass was not determined. The biomass data were taken after drying the wheat bundles. The grain was cleaned before weighing to determine yield and test weight. Grain nitrogen content and protein analysis were done by NIR spectroscopy, using a Technicon InfraAlyzer, Model 400 (Tarrytown, NY). Whole-wheat samples (9 g) were cleaned and allowed to equilibrate under room conditions for one week. The grain samples were ground on a Udy Cyclone Sample Mill (1 mm screen) with a Udy sample Mill Feed Controller (Fort Collins, CO), after pre-warming the mill for 1 hr. Calibration for protein and moisture was achieved by Kjeldahl N determination and air-oven moisture assays of every twentieth sample.

The straw was ground using a Wiley mill and bottle crusher to produce samples that passed a 140-mesh sieve (100um). Total straw N was determined by an automated dry combustion analyzer for N analysis. Total N per unit area was calculated by adding the amount of N in grain and straw at maturity. Due to the lack of soil data, it was not possible to apply Moll's (1982) method of calculating nitrogen use efficiency (NUE). Hence, NUE was determined using the difference method, where % NUE is equal to ((harvested-N_1 - harvested-N_0)/ Fertilized-N_1)*100, in which N_1 and N_0 refer to fertilized and unfertilized conditions, respectively. N utilization use efficiency, grain nitrogen, straw nitrogen and total nitrogen were used for the analysis in experiments I and II.

Statistical analysis

Grain yield, N-use efficiency, N-utilization efficiency, grain N, straw N, total N, and INSEY were subjected to analysis of variance. Due to similarity in results for INSEY, EY, and NDVI, this report is focused primarily on EY for 1999 and INSEY for 2000. Effects associated with groups, lines, cultivars and N treatments in Experiment I and II were considered as fixed. Correlations between grain yield and biomass with INSEY were determined to identify their association. Correlations were also determined between INSEY and N-use efficiency, N-utilization efficiency, grain nitrogen, straw nitrogen, and total nitrogen. Regression lines were fitted to explain the relationship of agronomic traits (yield, biomass) and INSEY, and to estimate the proportion of variation in yield, biomass, and NUE expressed by INSEY among the different wheat lines and cultivars.

CHAPTER IV

RESULTS AND DISCUSSION

Linear regression analysis of yield on EY in 1999, involving 96 random F_4 to F_6 experimental wheat lines, showed a positive slope and R^2 of 43% at Stillwater (Figure 2), however EY accounted for a much smaller proportion of the variation for yield at Lahoma, which had an R^2 of 14% (Figure 3). This disparity underscores the impact of environment on the type and strength of association between EY and yield.

In Experiment I, significant genetic variation was observed for grain yield, biomass, NUTE, GN, SN, and INSEY (P = 0.01 or 0.05) at Stillwater or Lahoma in 2000 (Table 1). Lines showed significant differences for yield, NUTE, GN, and SN at Stillwater, but at Lahoma, lines showed significant differences for all traits considered. The check cultivars also varied for yield, INSEY, and GN at Stillwater and Lahoma, and also for biomass at Stillwater. Lines and check cultivars were different for yield and INSEY at both locations. Surprisingly, no variation was found among the three EY-selected groups for all agronomic traits and INSEY at either Stillwater or Lahoma (Table 1). Grain yield varied from 1700 to 2778 kg ha^{-1}at Stillwater and from 1186 to 3135 kg ha^{-1} at Lahoma, (Table 2). Each of the three groups (high, medium and low) contained lines with a range in yield. The lines with the lowest and the highest yields were found in group I (high) at Stillwater. At Lahoma, the lowest yield was in group I and the highest yield was obtained from three different lines in each of the groups. This indicates that the low consistency of lines in EY groups from location to location and the lack of a yield response to selection for EY.

No significant correlation was found among lines for yield and biomass versus INSEY1, INSEY2, and INSEY3 at Stillwater and Lahoma, except for a weak, negative correlations were found for yield and INSEY-1 at Lahoma (P = 0.01) (Table 3). Significant correlations were found between NUTE, SN, TN versus and one of the INSEY measurements at Stillwater. At Lahoma, only NUTE and GN showed a significant correlation with INSEY and only with the first sensor reading. The two locations (Stillwater and Lahoma) showed different correlation patterns for the various agronomic traits with INSEY, indicating a strong environmental influence on INSEY expression (see Table 3).

Unlike the 1999 nursery results, negative associations of yield with INSEY were found from the regression analysis in 2000. No relationship between grain yield or biomass with INSEY was found at either location (Figures 4 and Figure 5).

In experiment II, cultivar variation and cultivar by nitrogen interactions for yield, biomass, NUE (data not shown), NUTE, GN, and INSEY were observed at Efaw (P = 0.01 or 0.05)(Table 4). N rates resulted in significant differences for yield and INSEY only at Hennesey. At both Efaw and Hennessey sufficient variability was observed among cultivars for yield and biomass. At Efaw, the mean grain yield at 0 kg ha^{-}

^{1} of N varied from 1683 kg ha^{-1} (2174) to 3143 kg ha^{-1} (Custer), whereas biomass ranged from 7122 kg ha^{-1} (Heyne) to 9232 kg ha^{-1} (Custer) (Table 5). At 90 kg ha^{-1} N, the yield ranged from 1758 kg ha^{-1} (Lockett) to 3813 kg ha^{-1} (OK96717), and biomass varied from 7449 kg ha^{-1} (Lockett) to 9662 kg ha^{-1} (Custer) (Table 6). At Hennessey the range in yield with the 0 N was 1854 kg ha^{-1} (Triumph) to 3409 kg ha^{-1} (Heyne), and with the 90 kg ha^{-1} N, the lowest yield was 1518 kg ha^{-1} (Longhorn) and the highest was 2977 kg ha^{-1} (2174) (Table 7). Due to unique weather and edaphic conditions suitable for the release of N in the soil, the performance of cultivars was not affected by the difference in applied N at Efaw. There were significant difference between the two N treatments for traits such as NUTE, TN, and INSEY at Efaw (Tables 4, 5, and 6) and for GN and INSEY at Hennessey (Table 7).

At Efaw significant relationships were found for yield and biomass versus all INSEY values under 0 kg N ha^{-1} (Table 3). However, weaker association was noted under the 90 kg N ha^{-1} treatment. Similar patterns were noticed at Hennessey where the correlation of yield and INSEY values, were significant under 0 kg N ha^{-1}. The strength of the associations with zero N between yield and INSEY and between biomass and INSEY increased from the first to the fourth INSEY readings. In addition, NUE was negatively correlated with INSEY 3 and INSEY 4, under O N at Efaw only. There was a relatively lower, but significant correlation of NUTE with INSEY across the two locations

(Efaw and Hennessey). Moreover, GN, SN, and TN had relatively significant and stronger correlations with INSEY values (Table 3). This supported the idea that NDVI and INSEY are dictated by the amount of available N in the plant.

The fitted regression lines showed a positive and negative relationship between yield and INSEY at Efaw under 0 and 90 kg N ha^{-1}, respectively (Figure 6). Thus the type of association was bi-directional depending on the amount of N available in the soil at Efaw. At Hennessey, a similar type of association occurred between yield and INSEY under the two N treatments, although with a much reduced R^2 from 0.45 to 0.10 under 0 and 90 N, respectively. At both N rates, the relationship between yield and INSEY was positive (Figure 7).

One can see the presence of variation for yield, biomass, NUE, NUTE, and INSEY among genotypes in both experiments. Not all INSEY measurements showed significant differences. In most of the results, INSEY1 or INSEY2 accounted for most of the variation among lines or cultivars. This can possibly be explained according to Carlson et al. (1997), who found that NDVI increases linearly with increasing leaf area index up to a certain level beyond which its sensitivity to leaf area index becomes weaker.

Variation in agronomic traits (yield, biomass, NUE) was not strongly reflected by variation in any of the INSEY measurements in either 1999 or 2000. Moreover, the association of yield and other agronomic traits with canopy reflectance measurements (EY, INSEY) was not consistent between locations. This was most evident in the difference in R^2 between Stillwater and Lahoma (Figures 2 and 3), which not only reflected a difference in location but also a possible difference in N status due to removal of forage by clipping at Stillwater before taking canopy reflectance measurements. A different association of yield and INSEY in 2000 (Figure 4) as compared to 1999 (Figure 2 and 3) was found at the same locations (Stillwater and Lahoma), only with a reduced number of lines (20) in 2000.

The impact of soil N on yield versus INSEY was most evident in Experiment II in which optimal and sub-optimal N rates were used. This experiment showed a positive association of yield and INSEY under a sub-optimal rate of N at both locations (Efaw and Hennessey). In contrast, an unpredictable association was found under optimal N rates at Stillwater, Lahoma, Efaw, and Hennessey (Figures 4, 6, and 7), regardless of genotypic sample. The experimental lines and cultivars showed similar associations for yield and biomass with INSEY for the same N treatments.

The classification of lines into groups selected for EY showed that EY or INSEY can be greatly impacted by location or soil N condition. This can be confirmed from the correlation analysis (not shown) for EY (1999) and INSEY (2000) at Stillwater, in which classifications of lines was found to be highly inconsistent. Lines selected for high EY in 1999 ranged from low to high in 2000 for INSEY, and visa versa.

In conclusion, the association obtained from canopy reflectance indices and agronomic traits varied from year to year and from location to location, a strong indication of low heritability for INSEY or EY. Variation in EY or INSEY among genotypes was apparently influenced more strongly by environmental factors than by genetic factors.

Table 1. Mean squares for agronomic traits and in-season estimated yield (INSEY) of experimental lines at Stillwater and Lahoma, OK in 2000.

Source	df	Grain yield	Biomass	INSEY sample 1	INSEY sample 2	INSEY sample 3	Nitrogen(N) utilization efficiency	Grain nitrogen	Straw nitrogen
		------ (kg ha^{-1})^{2}------		---------- x 10^{-7} ---------				---- (kg ha^{-1})^{2} ----	
Stillwater									
Entries	24	310137**	827159*	1.91**	0.11	1.62	27.3**	109**	100**
Lines	19	269312**	691604	1.32	0.12	1.57	27.3**	97**	101**
Groups	2	20226	284087	2.08	0.11	0.19	8.7	94	154
Lines(Groups)	17	298616	739547	1.20	0.12	1.74	29.5	97	95
Checks	4	310704*	1342768**	2.85 *	0.07	1.87	9.7	107**	37
Line vs check	1	1083552**	1340276*	9.20**	0.05	1.59	107.4	349	32
Residual	72	48121	498555	0.83	0.12	1.90	6.2	23	42
Lahoma									
Entries	24	1046324**	7570196**	0.30**	1.83**	0.07**	54.6**	338**	86**
Lines	19	1006820**	8993505**	0.28**	2.12**	0.07**	56.9*	336**	569**
Groups	2	534385	2247923	0.95	6.79	0.09	56.8	419	212
Lines(Groups)	17	1062401	9787103	0.20	1.57	0.07	56.9	325	611
Checks	4	266670**	2631985	0.40**	0.88	0.08**	13.7	139**	197
Line vs check	1	4915523**	280158	0.28**	0.10	0.00	175.6	119	67
Residual	72	60839	3627328	0.06	0.16	0.01	7.2	21	212

*, ** Significant at P = 0.05 and 0.01, respectively.

Table 2. Means for agronomic traits and in-season estimated yield (INSEY) of 20 experimental lines and 5 checks at Stillwater and Lahoma, OK in 2000.

		Stillwater					Lahoma				
Selection Group	Entry	Grain yield	Biomass	INSEY sample			Grain yield	Biomass	INSEY sample		
				1	2	3			1	2	3
		---- kg ha^{-1}----		--------- x 10^{-3} ---------			--- kg ha^{-1}------		--------- x 10^{-3} ---------		
High	1	2548	8071	6.83	6.64	5.14	2434	12629	8.07	7.21	5.98
High	2	2318	7948	6.91	6.73	5.22	2020	11482	7.96	7.05	5.92
High	3	1700	7206	7.19	6.78	5.29	2698	12683	8.25	7.27	5.97
High	4	2671	8148	6.85	6.67	5.05	2566	13827	8.09	7.21	5.95
High	5	2484	8623	6.79	6.71	5.08	2279	12097	8.02	7.11	5.93
High	6	2159	8161	7.29	6.76	4.93	1186	14274	8.22	7.28	6.01
High	7	2338	7977	7.11	6.80	5.58	2046	12470	8.12	7.28	6.01
High	8	2778	8716	7.09	6.79	5.14	3135	14502	8.03	7.13	5.93
Medium	9	2619	8352	6.90	6.73	4.99	1966	10824	8.20	7.35	6.04
Medium	10	2058	8263	7.31	6.79	5.07	2557	11850	8.20	7.30	5.99
Medium	11	2240	8822	7.08	6.70	5.30	2349	12189	8.16	7.16	5.93
Medium	12	2576	8504	7.02	6.62	5.21	2217	10813	8.13	7.20	5.87
Medium	13	2417	7844	6.86	6.73	5.37	3007	12200	8.10	7.23	5.99
Medium	14	2348	7906	6.86	6.77	4.75	2949	13130	8.13	7.24	5.98
Medium	15	2188	7586	6.84	6.68	5.04	3112	13083	8.04	7.23	5.94
Medium	16	2716	8409	6.79	6.70	5.35	2771	13849	8.15	7.26	5.98
Low	17	2253	8053	7.02	6.71	5.30	2225	10945	8.09	7.21	5.94
Low	18	2651	8711	7.02	6.76	5.40	3075	11925	8.00	7.18	5.97
Low	19	2524	8660	7.35	6.79	5.15	1971	11255	8.23	7.33	6.00
Low	20	2317	7910	7.22	6.79	4.87	2888	16958	8.22	7.26	6.03
Check	Jagger	2595	7920	6.81	6.69	5.14	3466	13701	8.11	7.24	6.02
Check	2174	2464	7800	7.11	6.77	5.18	3026	12471	8.21	7.29	6.04
Check	2137	2350	7123	6.40	6.67	5.27	2802	13227	7.96	7.16	5.96
Check	Cimarron	3038	8753	6.90	6.71	5.08	2933	11570	7.99	7.21	5.98
Check	Custer	2830	7924	6.67	6.74	5.63	2907	12940	8.12	7.25	5.97

Table 3. Correlation of agronomic traits with in-season estimated yield (INSEY) at Efaw, Hennessey, Stillwater & Lahoma, OK, under 0 and 90 kg ha^{-1} N rates in 2000.

N rate†		INSEY	Grain yield	Biomass	Harvest index	N-use efficiency ‡	N-utilization efficiency	Grain nitrogen	Straw nitrogen	Total nitrogen
90	ST	1	-0.17	0.18	-0.66**	-	-0.27**	-0.11	0.28**	0.15
		2	-0.14	0.04	-0.33	-	-0.41**	0.01	0.43**	0.36**
		3	0.07	0.08	-0.16	-	-0.10	0.11	0.21*	0.24**
90	LA	1	-0.24**	-0.11	-0.34	-	-0.20*	-0.20*	0.04	-0.06
		2	-0.16	-0.19	-0.11	-	-0.06	-0.13	-0.06	-0.12
		3	0.01	0.15	-0.08	-	-0.11	0.03	0.15	0.15
0	EF	1	0.27*	0.33**	-0.02	-0.22	-0.11	0.24*	0.30**	0.30**
		2	0.46**	0.71**	-0.25*	-0.41	-0.37**	0.53**	0.61**	0.65**
		3	0.49**	0.77**	-0.29**	-0.56**	-0.40**	0.60**	0.64**	0.70**
		4	0.48**	0.79**	-0.35**	-0.47*	-0.40**	0.58**	0.65**	0.70**
90	EF	1	-0.17*	-0.25	-0.07	-0.25	-0.02	-0.29**	-0.07	-0.19
		2	-0.22*	-0.21*	-0.16	-0.31	-0.03	-0.31**	-0.08	-0.21
		3	-0.19	-0.08	-0.24*	-0.20	-0.38**	-0.08	0.30**	0.20
		4	-0.10	0.06	-0.23*	-0.16	-0.31** -	0.25**	0.19	-
0	HS	1	0.52**	-	-	-	-	0.54**	-	-
		2	0.51**	-	-	-	-	0.60**	-	-
		3	0.50**	-	-	-	-	0.61**	-	-
		4	0.58**	-	-	-	-	0.69**	-	-
90	HS	1	0.23*	-	-	-	-	0.23	-	-
		2	0.10	-	-	-	-	0.25**	-	-
		3	0.29**	-	-	-	-	0.39**	-	-
		4	0.30**	-	-	-	-	0.40**	-	-

*, ** Significant at P = 0.05 and 0.01 respectively.

† ST, LA, EF and HS stands for Stillwater, Lahoma, Efaw and Hennessey

‡ Correlation coefficients for nitrogen use efficiency were calculated from the average of four replications.

Table 4. Mean squares for agronomic traits and in-season yield estimates (INSEY) and other traits for 20 winter wheat cultivars grown at Efaw and Hennesey, OK in 2000

Source	df	Grain Yield	Biomass	INSEY samples 1	INSEY samples 2	INSEY samples 3	Nitrogen (N) Utilization efficiency	Nitrogen (N) Grain	Nitrogen (N) Straw	Nitrogen (N) Total
		---------kg ha^{-1}----------		----------- x 10^{-7} ---------				------------ kg ha^{-1} ------------		
Efaw										
Nitrogen (N)	1	263060	7086585	171.7**	43.2	113.2*	4698**	1091	20332*	30817*
N X replication	3	393936	9212976	3.4	4.8	10.6	90	197	1030*	1594
Cultivar(C)	19	870300**	2028803**	10.9**	1.0**	2.8**	86**	202**	151	264
N x C	19	212756**	1362080*	3.6	0.5	1.5**	39**	101*	122	306
C X replication	113	98633	832532	3.9	0.5	0.6	16	52	78	186
Hennessey										
Nitrogen (N)	1	18675607*	-	333.3**	143.9*	795.5*	-	249	-	-
N X replication	3	716227	-	9.4	5.1	31.5	-	308	-	-
Cultivar (C)	19	1104576**	-	27.9**	7.4*	10.4**	-	386**	-	-
N x C	19	304619**	-	13.2	3.6	5.6*	-	105**	-	-
C X replication	113	117744	-	6.5	4.3	2.9	-	47	-	-

*, ** Significant at P = 0.05 and 0.01, respectively.

Table 5. Means for agronomic traits, nitrogen use efficiency, nitrogen utilization efficiency and in-season estimated yield (INSEY) of wheat cultivars grown under 0 kg ha^{-1} N at Efaw, OK in 2000.

Cultivar	Grain Yield	Biomass	Harvest index	Nitrogen use efficiency†	N-utilization efficiency	Total nitrogen	In-season yield estimates (INSEY)		
							1	2	3
	------ kg ha^{-1} ------					-- kg ha^{-1} --	-------------- x 10^{-4} --------------		
Triumph 64	2561	8488	0.30	-	35.80	73.01	69.58	81.97	69.02
Chisholm	2966	8684	0.34	0.24	37.85	78.37	89.43	86.86	74.46
Plainsman V	2154	7373	0.29	-	27.31	80.10	83.45	85.41	73.83
Karl 92	2092	7122	0.29	0.25	33.75	64.10	81.04	84.06	70.94
Longhorn	1922	8393	0.23	0.30	28.20	69.40	79.27	85.74	72.44
Custer	3143	9232	0.34	0.26	39.16	80.74	81.17	85.05	72.35
Jagger	2746	8264	0.33	0.28	41.24	66.96	82.38	85.47	71.29
Ogallala	2791	8713	0.32	0.36	31.76	89.57	82.59	84.87	71.64
Agseco	2383	7261	0.33	0.43	37.88	63.43	75.01	79.85	60.47
2137	3122	8663	0.36	0.33	45.06	69.56	75.48	84.77	72.03
2174	1683	5359	0.24	0.42	27.24	48.77	61.33	62.33	51.31
Lockett	2520	8137	0.31	0.28	37.38	71.83	79.47	82.86	69.70
Heyne	2111	7095	0.30	0.38	35.38	60.58	83.41	85.44	67.82
Trego	2548	8065	0.32	0.38	35.34	76.63	80.84	85.62	71.14
Oro Blanco	2385	8479	0.28	-	29.02	83.16	79.02	87.58	73.44
Thunderbolt	2710	8279	0.33	0.32	39.27	70.99	75.38	82.70	68.17
Intrada	2873	8889	0.32	-	34.72	84.26	82.59	86.38	75.00
OK94P549-2C	2522	8590	0.30	0.36	35.89	72.74	82.02	84.80	72.75
Ok101	2800	8557	0.33	0.39	42.59	66.02	81.07	84.65	70.86
OK96717	3003	9170	0.33	0.24	36.55	82.28	80.43	84.34	71.72
$LSD_{(0.05)}$	4.96	1517	0.05	0.09	6.94	19.4	12.00	11.00	10.00

† unequal number of replications was used to calculate nitrogen use efficiency.

Table 6. Means for agronomic traits, nitrogen utilization efficiency and, in-season estimated yield (INSEY) of wheat cultivars grown under 90 kg ha^{-1} nitrogen at Efaw, OK in 2000.

Cultivar	Grain Yield	Biomass	Harvest index	N-utilization efficiency	Total nitrogen	In-season yield estimates (INSEY)		
						1	2	3
	------- kg ha^{-1} ------				-- kg ha^{-1} --	--------------- x 10^{-4} ---------------		
Triumph 64	2578	8594	0.30	30.0	86.2	81.67	87.74	75.62
Chisholm	2631	8825	0.30	26.2	100.5	92.45	87.85	77.04
Plainsman V	2106	8088	0.26	23.2	91.6	83.37	86.92	75.41
Karl 92	2611	8542	0.31	28.6	91.7	88.91	88.43	76.71
Longhorn	1884	8858	0.21	18.3	103.0	85.90	87.84	76.43
Custer	3267	9662	0.34	30.1	109.3	84.93	86.84	76.10
Jagger	2212	8042	0.27	22.6	98.6	86.08	88.22	77.11
Ogallala	2630	9409	0.28	26.8	106.6	80.68	87.41	75.73
Agseco	2695	9182	0.29	25.1	111.5	85.55	87.47	73.68
2137	2865	9144	0.31	29.9	98.9	82.53	87.46	75.98
2174	2672	9453	0.28	24.0	112.9	86.50	88.02	76.48
Lockett	1758	7449	0.23	19.2	93.9	91.80	87.53	76.02
Heyne	2191	8168	0.27	23.9	95.2	92.95	89.68	77.60
Trego	2650	9269	0.29	25.8	108.2	80.19	87.60	76.33
Oro Blanco	1863	7577	0.25	22.2	85.4	86.53	89.26	76.55
Thunderbolt	2754	9099	0.30	26.3	107.1	80.37	86.62	75.53
Intrada	2462	8109	0.30	26.1	94.9	93.30	89.55	77.20
OK94P549-2C	2654	9024	0.30	23.8	113.3	89.00	87.85	76.45
Ok101	2585	8460	0.31	24.2	110.1	89.29	87.44	76.57
OK96717	2813	9214	0.31	25.9	109.7	92.22	87.86	76.49
$LSD_{(0.05)}$	340	922	0.02	3.8	15.4	7.00	1.00	1.00

Table 7. Means for grain yield, grain nitrogen, and in-season estimated yield (INSEY) of wheat cultivars grown under 0 kg ha^{-1} and 90 kg ha^{-1} N at Hennessey, OK in 2000.

Cultivar	0 kg ha^{-1} N					90 kg ha^{-1} N				
	Grain Yield	Grain nitrogen	In-season estimated yield (INSEY)			Grain yield	Grain nitrogen	In-season estimated yield (INSEY)		
			1	2	3			1	2	3
	-----kg ha^{-1}-----		---------- x 10^{-4} ---------			-----kg ha^{-1}-----		---------- x 10^{-4} ---------		
Triumph 64	1854	33.71	54.92	73.69	51.52	1800	40.97	84.59	84.29	78.35
Chisholm	2354	41.22	68.75	77.86	57.31	1701	36.91	85.22	74.21	72.31
Plainsman V	2358	47.43	78.10	84.66	73.05	1962	48.96	75.96	86.98	79.81
Karl 92	2568	47.94	67.51	73.29	68.49	2438	54.29	80.24	81.49	79.09
Longhorn	2028	41.41	74.10	74.82	64.32	1518	38.28	81.63	86.80	79.79
Custer	2745	49.44	73.87	73.69	63.58	2223	48.67	77.03	81.54	68.00
Jagger	3383	61.63	89.22	84.59	70.88	2077	45.94	95.02	84.63	79.86
Ogallala	2551	51.24	68.05	76.84	59.08	2400	58.28	84.77	86.77	77.81
Agseco	2475	46.14	75.24	80.73	52.57	1593	38.91	71.51	86.15	76.38
2137	2978	49.92	73.56	81.22	65.54	2077	45.64	79.73	87.94	79.40
2174	3235	59.52	73.54	79.63	66.59	2977	67.85	88.36	88.34	80.01
Lockett	2457	44.93	79.37	79.49	63.58	1689	39.28	83.69	87.48	76.11
Heyne	3409	63.55	86.19	83.87	68.88	2008	46.78	95.69	89.17	80.88
Trego	3126	55.91	73.71	80.09	62.11	2294	51.81	85.76	80.21	79.41
Oro Blanco	2981	51.44	80.69	82.65	67.22	1711	38.16	74.70	87.98	78.73
Thunderbolt	2567	50.03	63.62	72.41	61.89	2199	52.47	70.74	85.44	76.91
Intrada	3321	56.31	76.02	80.64	63.21	2389	52.85	84.31	87.86	80.04
OK94P549-2C	3239	57.52	73.03	79.04	66.25	2716	60.56	88.07	84.37	79.75
Ok101	3119	50.31	74.66	79.95	68.14	2251	47.30	87.53	81.05	77.36
OK96717	3147	55.84	76.55	79.31	62.62	2258	50.76	88.67	85.57	78.84
$LSD_{(0.05)}$	426	7.73	9.00	6.00	6.00	384	8.52	10.00	9.00	7.00

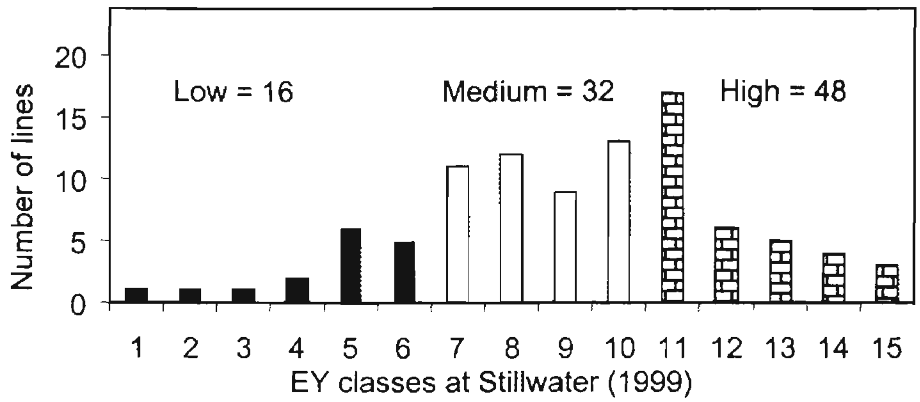

Figure 1. Distribution of wheat lines designated by low, medium and, high EY at Stillwater, OK in 1999.

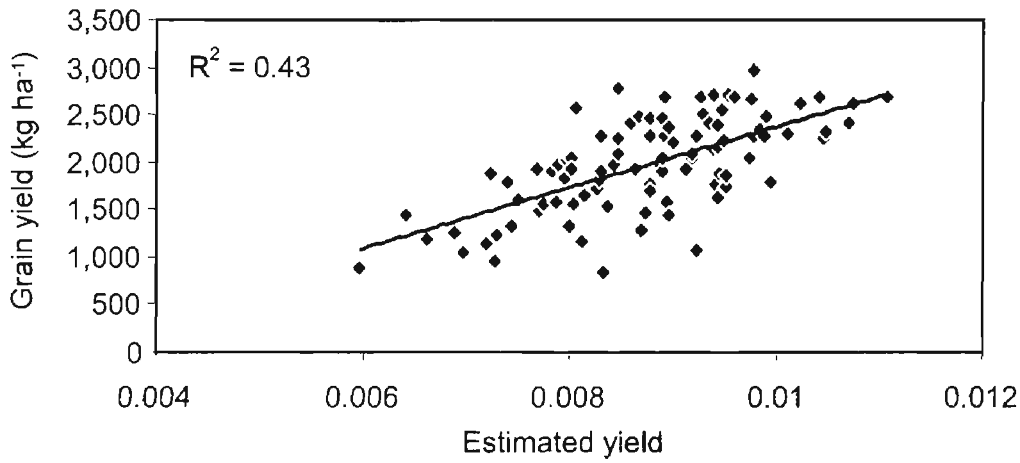

Figure 2. Association of grain yield and estimated yield (EY) at Stillwater, OK in 1999 among 96 wheat lines.

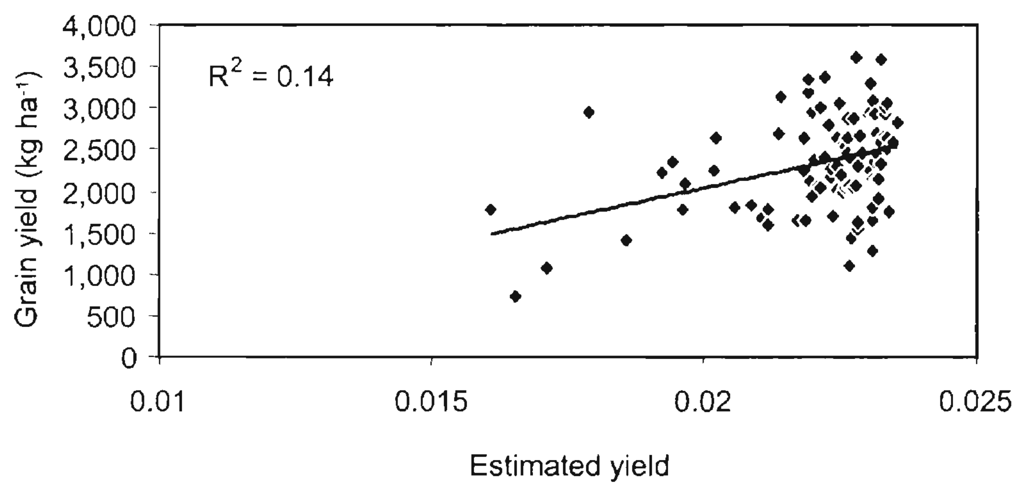

Figure 3. Association of grain yield and estimated yield (EY) at Lahoma, OK in 1999 among 96 wheat lines

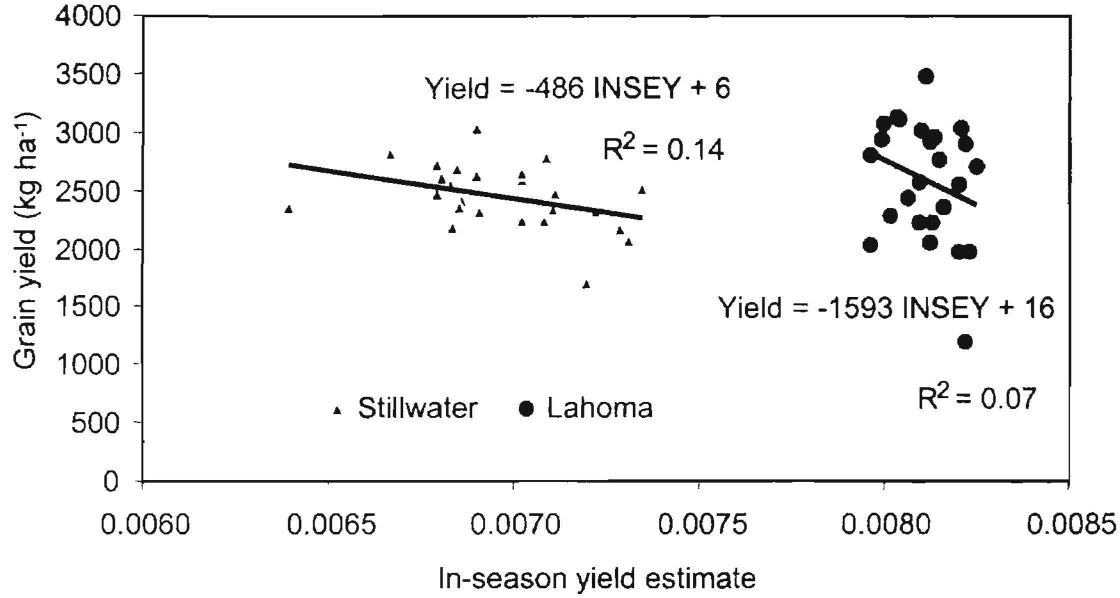

Figure 4. Association of grain yield and in-season estimated yield (INSEY) at Stillwater and Lahoma, OK among 20 wheat lines in 2000

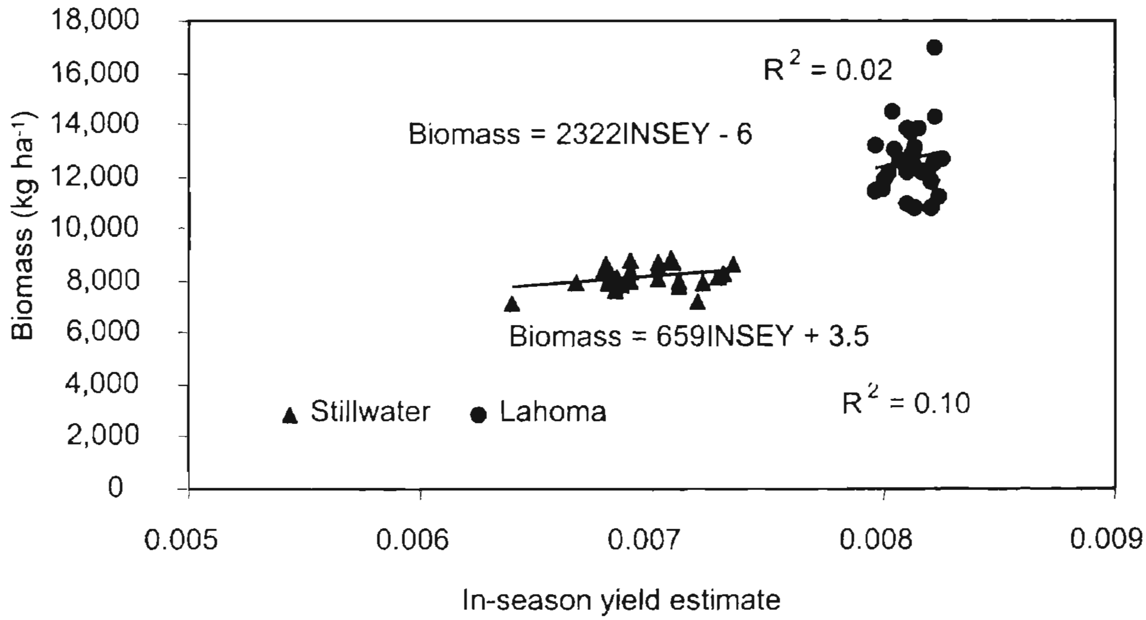

Figure 5. Association of biomass and in-season estimated yield (INSEY) at Stillwater and Lahoma, OK among 20 wheat lines in 2000

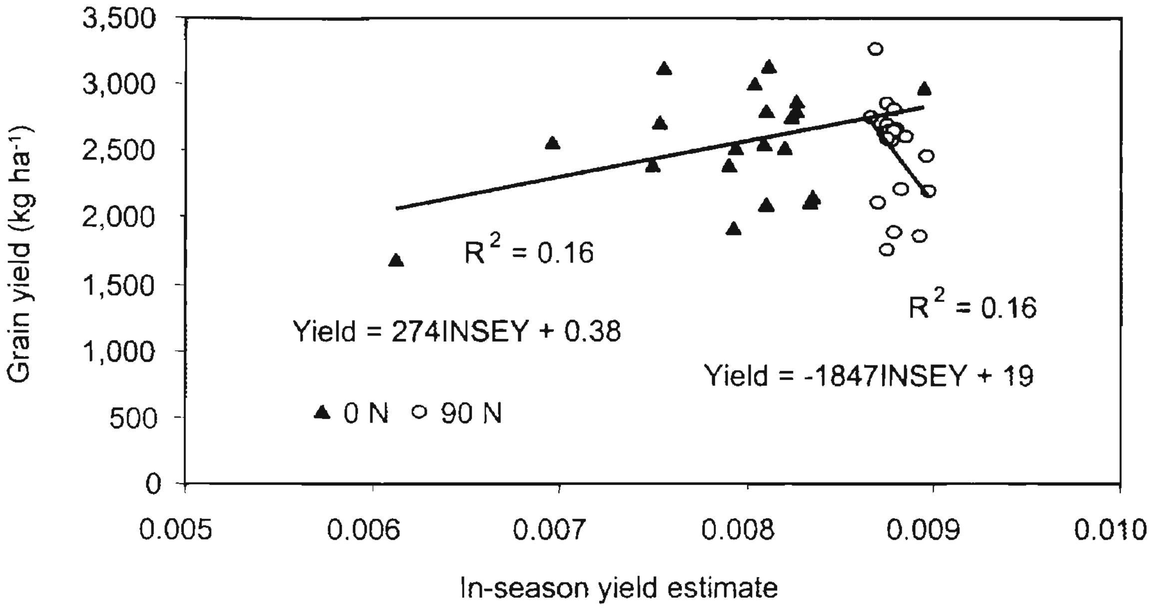

Figure 6. Association of grain yield and in-season yield estimates using 20 wheat cultivars under 0 and 90 kg ha^{-1} N at Efaw in 2000

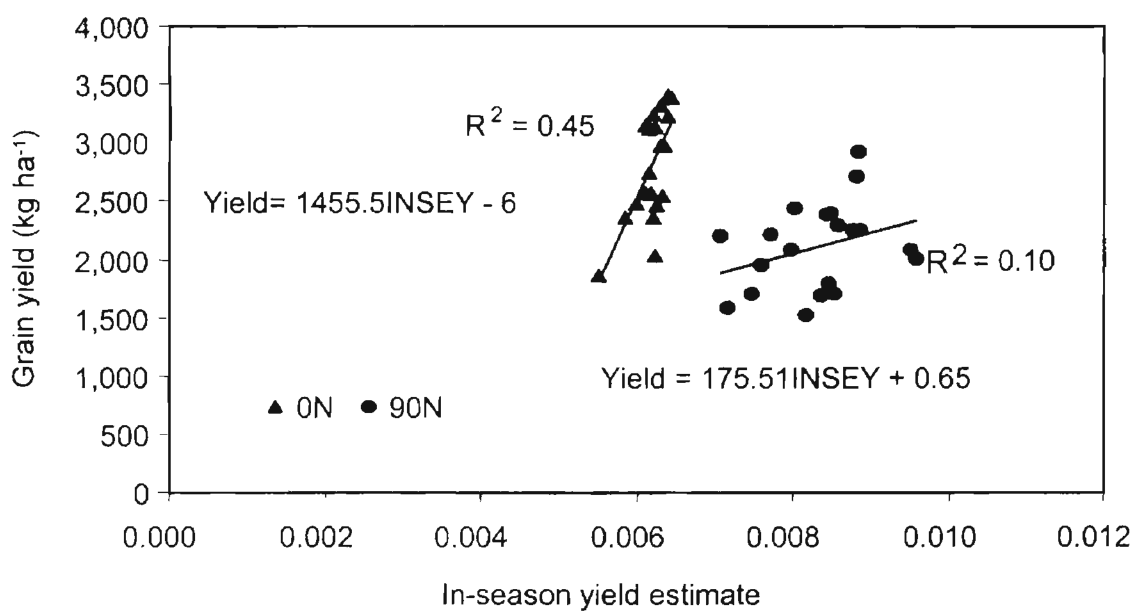

Figure 7. Association of grain yield and in-season estimated yield (INSEY) among 20 wheat cultivars under 0 and 90 kg ha^{-1} N at Hennessey, OK in 2000

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Appendix A. Winter wheat lines and cultivars (*Triticum aestivum L.*) for Experiment I grown at Stillwater and Lahoma, OK in 2000

No.	Pedigree/Parentage	Estimated yield (EY) in 1999 (Stillwater)	Grouping by EY
1	Karl 92/MV21 F4:8	0.01108	High
2	Tonkawa/GK50 F4:8	0.01047	High
3	KS831862/6/Ctk/3/A66/Cmn/2/TX2607-6/4/NE7060 F3:7	0.00995	High
4	Tonkawa/GK50 F4:8	0.00985	High
5	Tonkawa/GK50 F4:8	0.00960	High
6	RS FORAGE C1X2:5 (97118322)	0.00946	High
7	Tonkawa/MV21 F4:8	0.00940	High
8	Tonkawa/GK50 F4:8	0.00919	High
9	Tonkawa/MV21 F4:8	0.00897	Medium
10	KS831862/6/Ctk/3/A66/Cmn/2/TX260 TX2607-6/4/NE7060 F3:7	0.00893	Medium
11	RS FORAGE C1X2:5 (97118346)	0.00889	Medium
12	83F35054#4/W81-171//N87vo77/Abilene F3:7	0.00877	Medium
13	Custer/Jagger F2:6	0.00863	Medium
14	KS92WGRC15/Tonkawa//Ponderosa F2:6	0.00842	Medium
15	KS831862/6/Ctk/3/A66/Cmn/2/TX2607-6/4/+ F3:7	0.00829	Medium
16	KS92WGRC15/Tonkawa//Ponderosa F2:6	0.00805	Medium
17	KS81W418/Stehpens//KS831936-3/NE86501 F3:7	0.00798	Low
18	W80-137/SR4685//N87V106 F3:7	0.00783	Low
19	RS FORAGE C1X2:4 (97118328)	0.00746	Low
20	RS FORAGE C1X2:4 (97118328)	0.0072	Low
21	Jagger	-	Check
22	2174	-	Check
23	2137	-	Check
24.	Cimarron	-	Check
25.	Custer	-	Check

Appendix B. Winter wheat cultivars (*Triticum aestivum L*) included in Experiment II grown at Efaw and Hennessey, OK in 2000

NO.	Cultivars	Parentage/ Pedigree	Year of release	Plant Stature
1.	Triumph 64	Blackhull/Kanred/3/Blackhull/Kanred/2/ Florence	1964	Tall
2.	Chisholm	Sturdy/Nicoma	1983	Short
3.	Plainsman V	-	-	Medium tall
4.	AG SECO 7853	-	1989	Tall
5.	Longhorn	N5260-1/Thunderbird	1990	Medium tall
6.	Karl 92	Plainsman V/3/Kaw/Atlas 50//Parker*5/Agent	1992	Medium
7.	Jagger	KS82W418/Stephens	1992	Medium
8.	Ogallala	TX 81V6187/Abilene	1992	Medium
9.	Custer	F29-76/TAM105//Chisholm	1994	Medium
10.	Oro Blanco	VONA/3/NAD63/C0652643//CTK/4/Oro Blanco	1994	Short
11.	2137	W2440/W9488A//2163	1995	Medium
12.	2174	IL 71-5662/PL 145//2165(=HBZ374C)	1997	Medium
13.	Lockett	-	1998	Tall
14.	Heyne	Plainsmanv/KS75216//SWM754308/3/Plainsman V/Lindon //KS82W44	1998	Medium
15.	Trego	KS87h325/Rio Blanco (=Ks95hw62-6)	1999	Medium
16.	Thunderbolt	Abilene/KS90W6RC10	1999	Medium Tall
17.	Intrada	Oro Blanco/Tam 200	2000	Medium
18.	Ok101	OK87W663/Mesa//2180	2001	Medium
19.	OK94p549-2c	HBY 756A/SXI//2180	-	Medium
20.	OK96717	Abilene/2180//Chisholm	-	Medium

Source: Watson, (2000).

Appendix C. Calendar date, growth stage, and growing-degree days for each NDVI measurements in Experiments I and II at four Oklahoma locations in 2000.

Location	Date of NDVI data collection				Feeke's growth stage for† NDVI sample Collection				Growing-degree days (GDD) ‡ at each NDVI collection			
	1	2	3	4	1	2	3	4	1	2	3	4
Stillwater	03/07	03/27	04/11	-	6	7-8	9-10	-	113	131	146	-
Lahoma	03/13	03/28	04/27	-	5	8-9	10	-	108	122	152	-
Efaw	03\07	03/27	04/11	04/27	5	7-8	8-9	9-10	82	100	115	131
Hennesey	03/13	03/28	04/07	04/28	5	7-8	8-9	9-10	85	99	110	131

† Feeke's growth stages 5, 6, 7, 8, 9, and 10 represent leaf sheath strongly erected, first node of stem visible, second node visible, last leaf just visible, and sheath of last leaf completely grown out, ear swollen but not yet visible, respectively.
‡ days from planting to sensing (days with GDD greater than 0°C)

Appendix D. Means for agronomic traits and spectral indices of three groups of wheat lines based on estimated yield (EY) and grown at Stillwater and Lahoma, OK in 2000.

Location	Selection Group	Grain yield	Biomass	INSEY sample 1	INSEY sample 2	INSEY sample 3	Grain nitrogen	Straw nitrogen	Total nitrogen
		----- kg ha^{-1} ------		---------------- 10^{-3} ------------------			---------------- $Kgha^{-1}$ --------------		
Stillwater	Check	3026	12782	8.07	7.22	5.99	59.52	62.93	122.42
	High	2304	12543	8.18	7.28	5.99	46.51	68.11	114.62
	Medium	2471	12872	8.12	7.22	5.99	51.14	67.52	118.53
	Low	2630	12311	8.04	7.17	5.99	54.70	56.90	111.60
Lahoma	Check	2655	7904	6.80	6.73	5.22	55.92	47.72	93.61
	High	2375	8706	7.03	6.72	5.13	50.44	44.51	94.62
	Medium	2395	8211	6.91	6.71	5.10	50.73	41.63	92.33
	Low	2436	8334	7.11	6.72	5.15	54.35	39.00	93.41

Appendix E. Correlations for agronomic traits versus in-season estimated yield (INSEY) within three selection groups at Stillwater and Lahoma, Ok in 2000.

	INSEY (Checks)			INSEY (High)			INSEY (Medium)			INSEY (Low)		
	1	2	3	1	2	3	1	2	3	1	2	3
Stillwater												
Grain yield	-0.07	-0.09	-0.13	-0.26	-0.29	-0.02	0.01	-0.05	0.15	-0.24	0.05	-0.02
Biomass	0.03	-0.05	0.12	0.09	0.00	0.03	0.38	0.09	0.27*	-0.06	0.16	-0.06
N utilization efficiency	-0.19	-0.20	-0.28	-0.38*	-0.65**	-0.21	-0.20	-0.38*	-0.02	-0.11	-0.22	0.03
Grain nitrogen	0.03	0.01	0.15	-0.27	-0.12	0.05	0.08	0.06	0.15	-0.16	0.19	0.01
Straw nitrogen	0.13	0.12	0.45**	0.48**	0.72**	0.32*	0.28*	0.49**	0.16	0.03	0.23	0.00
Total nitrogen	0.11	0.09	0.41	0.25	0.56**	0.33*	0.26	0.42*	0.20	-0.05	0.24	0.01
Lahoma												
Grain yield	0.08	-0.04	0.21	-0.17	-0.20	-0.33	-0.46**	-0.26	-0.01	-0.45	-0.60*	0.02
Biomass	-0.14	-0.30	-0.11	-0.07	-0.11	0.04	-0.37*	-0.28	0.19	0.19	-0.07	0.44
N utilization efficiency	0.17	0.03	0.18	-0.15	0.13	0.28	-0.20	-0.03	-0.13	-0.71**	-0.46*	-0.50*
Grain nitrogen	0.40	0.24	0.38	-0.26	-0.25	-0.37*	-0.35*	-0.20	0.05	-0.52*	-0.62**	-0.07
Straw nitrogen	-0.27	-0.17	-0.18	0.08	0.05	0.12	-0.13	-0.17	0.16	0.45	0.05	0.62**
Total nitrogen	-0.06	-0.04	0.00	-0.05	-0.08	-0.07	-0.26	-0.23	0.17	0.20	-0.19	0.51*

* , ** Significant at P = 0.05 and 0.01, respectively.

Appendix F. Mean of agronomic traits, protein content and percent protein of wheat at Stillwater and Lahoma, OK in 2000

	Stillwater						Lahoma				
Entry	Test weight	Heading date	Maturity date	Height	Grain protein	Straw protein	Test weight	Heading date	Maturity date	Grain protein	Straw protein
	Kg hl^{-1}	------d------		-- cm --	------- %	----------	Kg hl^{-1}	------d------		------ %	-----
1	73.6	21	56	96	12.0	4.2	71.5	27	59	12.0	3.7
2	72.1	25	59	90	12.9	4.6	73.8	32	64	13.0	3.4
3	69.3	28	58	79	12.8	6.2	69.7	33	63	11.2	4.2
4	74.8	22	58	85	11.9	4.6	73.9	29	60	11.3	4.3
5	72.7	25	61	96	12.5	4.1	75.3	32	63	12.9	3.4
6	76.4	24	62	93	11.8	4.6	71.4	28	61	11.3	4.4
7	73.7	21	55	95	12.3	5.1	73.4	27	59	12.3	4.0
8	70.8	21	57	84	11.8	5.5	73.9	28	61	10.7	4.0
9	73.3	22	57	95	12.0	4.2	73.0	27	60	12.8	4.7
10	70.0	27	62	86	12.6	4.4	68.8	33	59	11.4	4.1
11	72.5	25	57	98	13.1	4.2	73.2	30	58	13.0	4.1
12	73.5	24	59	89	12.1	4.3	70.2	29	57	11.5	4.4
13	71.6	19	55	83	12.0	5.0	72.5	26	59	10.8	3.6
14	71.4	22	54	84	11.8	5.2	71.4	27	58	11.3	3.9
15	73.8	24	55	76	12.9	4.7	74.1	29	60	11.6	3.4
16	72.2	18	52	86	11.3	4.1	72.2	26	56	11.5	4.4
17	68.4	23	55	88	13.4	4.9	71.1	27	58	13.1	4.1
18	71.8	21	57	90	12.7	4.1	71.6	26	57	12.2	3.5
19	72.0	15	56	95	12.8	3.8	66.1	23	53	12.2	4.2
20	73.4	16	53	95	12.5	3.7	69.2	23	54	12.0	4.1
21	74.6	14	52	81	12.9	3.9	74.5	24	54	10.9	3.9
22	76.3	20	54	84	12.9	4.3	74.9	27	58	12.4	4.1
23	73.6	21	56	84	11.6	5.3	73.4	28	59	10.6	4.3
24	74.8	15	54	90	11.6	4.5	73.5	26	56	11.2	3.8
25	75.0	17	53	86	11.8	4.5	72.3	25	57	11.5	4.0

Appendix G. Ranks for yield, biomass, and in-season estimated yield (INSEY), and diseases reactions of wheat lines and checks at Stillwater and Lahoma, OK in 2000.

	Stillwater					Lahoma					Stillwater/Lahoma		
Entry	Grain yield	Biomass	INSEY			Grain yield	Biomass	INSEY			Disease Reaction		
			1	2	3			1	2	3	Leaf rust †	BYDV‡	SG§
1	10	13	20	24	16	16	12	18	15	11	60-80S	4	7
2	19	16	13	13	10	22	21	24	25	24	40MS	4	6
3	25	24	4	6	8	13	11	1	7	14	40-80S	1	6
4	5	12	18	23	20	14	5	16	18	18	60-80S	4	6
5	12	6	22	16	17	18	17	21	24	22	30-40MS	4	6
6	23	11	3	9	23	25	3	4	5	5	80S	4	7
7	17	15	7	1	2	21	14	12	6	6	60S	4	7
8	3	3	8	2	15	2	2	20	23	21	80S	4	6
9	7	9	14	12	22	24	24	7	1	1	40MS	3	6
10	24	10	2	5	19	15	19	6	3	8	30MS	2	6
11	21	1	9	18	6	17	16	8	22	23	40MS	4	7
12	9	7	12	25	11	20	25	11	19	25	5R	4	5
13	14	21	16	14	4	6	15	15	13	9	60S	3	7
14	15	20	17	7	25	7	8	10	12	13	20MS	2	5
15	22	23	19	21	21	3	9	19	14	19	10MS	2	5
16	4	8	23	19	5	12	4	9	8	10	30MS	4	7
17	20	14	11	17	7	19	23	17	16	20	40MS	3	6
18	6	4	10	10	3	4	18	22	20	16	30MS	3	6
19	11	5	1	4	13	23	22	2	2	7	30-60MS	3	7
20	18	19	4	3	24	10	1	3	9	3	60-80S	4	8
21	8	18	21	20	14	1	6	14	11	4	80S	3	8
22	13	22	6	8	12	5	13	5	4	2	30-40MS	5	5
23	16	24	25	22	9	11	7	25	21	17	40-80S	4	7
24	1	2	15	15	18	8	20	23	17	12	60-80S	4	8
25	2	17	24	11	1	9	10	13	10	15	40-80S	4	7

† Leaf rust records from Stillwater and Lahoma using modified Cobb scale

‡ Barley yellow dwarf disease rated as 1 if susceptible and 5 if resistant.

§ Stay green character recorded on flag leaf (FL): 5, 6, 7, 8, and 9 means FL mostly green, partially chlorotic , mostly chlorotic, severely chlorotic, and dead, respectively.

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VITA

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