OPTICAL AND HUMAN ASSESSMENT OF WINTER WHEAT CULTIVARS FOR COMPETITIVENESS AGAINST JOINTED GOATGRASS, AND CHARACTERIZING OKLAHOMA JOINTED GOATGRASS-WINTER WHEAT HYBRIDS

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Bachelor of Science

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Stillwater, Oklahoma

1998

Submitted to the Faculty of the Graduate
College of the Oklahoma State
University in partial fulfillment of
the requirements for the Degree of
DOCTOR OF PHILOSOPHY
August 2003

OPTICAL AND HUMAN ASSESSMENT OF WINTER

WHEAT CULTIVARS FOR COMPETITIVENESS

AGAINST JOINTED GOATGRASS, AND

CHARACTERIZING OKLAHOMA

JOINTED GOATGRASS-WINTER

WHEAT HYBRIDS

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ACKNOWLEDGEMENTS

Foremost, I thank God for giving me the strength, wisdom, patience, and endurance to complete this degree. I express immense gratitude to my husband, Caleb, for his love, patience, understanding, encouragement, and assistance throughout the course of my graduate work. A special thanks to my sons, Seth and Jared, for their smiles and giggles that kept me entertained. I thank my parents, John and Lou, and my sister, Deborah, for their support and encouragement.

I would like to extended my sincere appreciation to my major advisor, Dr. Thomas Peeper, for his time, guidance, and constructive criticism throughout the course of my research. Appreciation is also extended to Dr. Eugene Krenzer, Dr. Marvin Stone, and Dr. John Solie for their assistance and participation as members of my graduate committee. I would like to thank the Oklahoma Wheat Commission and National Jointed Goatgrass Steering Committee for partial funding of these projects.

Gratitude is extended to the Department of Plant and Soil Sciences and the Department of Biosystems and Agricultural Engineering at Oklahoma State University for providing all the necessary facilities and equipment needed for this research. I am indebted to the Small Grains Weed Science crew; Jason Kelly, Caleb Stone, Johnny Roberts, Matt Barnes, Chad Trusler, Andy Hollon, Joey Collins, Kylie Vincent, Sandy Stanton, Amber Roberson, Deborah Solie, Emalee Friend, and Brian Wendlandt whose assistance and hard work made this research possible.

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CHAPTER I

COMPETITIVE ABILITY OF TWENTY-FOUR WINTER WHEAT (*Triticum aestivum* L.) CULTIVARS AGAINST JOINTED GOATGRASS (*Aegilops cylindirca* Host.).

Abstract: Characteristics other than mature height are known to contribute to competitive ability of wheat, but the literature has not identified specific traits that can be used to estimate competitive ability of hard red winter wheat. In field research with 24 winter wheat cultivars at five environments over two years, 1999-2001, wheat yields were not affected by jointed goatgrass (Aegilops cylindrica Host.) inteference at four of five environments. At the fifth environment, yield loss ranged from 45.2 to 13.4 % depending on cultivar. Cultivars varied substantially in their ability to suppress jointed goatgrass spikelet production. 'Scout 66' suppressed jointed goatgrass more than 'Heyne', 'TAM 202', and '2163' at all five environments. Wheat stand density seven to 10 days after seeding varied greatly with environment and appeared to be related to competitive ability. Wheat forage production was a minor factor in suppressing jointed goatgrass spikelet production. Wheat height measured at Zadocks 32 was inversely related to reduction in jointed goatgrass spikelet production, but not as much as wheat height at Zadocks 37. Wheat height at Zadocks 91 was inversely related to jointed goatgrass spikelet production, while wheat spike density was not. Wheat yield was variably related to jointed goatgrass spikelet production.

The Hühn's statistic demonstrated that rankings of the 24 wheat cultivars for wheat stand density, forage production, wheat height at Zadocks 32, 37, and 91, wheat spike density, and jointed goatgrass spikelet production were not unstable across the environments sampled and were not unstable within an environment. Thus environment did not have a major impact on a cultivar's competitive ability. The implicated wheat attributes of stand density, wheat height at Zadocks 37, and wheat yield should be useful in assessing competitive ability of a wheat cultivar regardless of environment sampled.

Nomenclature: Winter wheat, *Triticum aestivum* L.; jointed goatgrass, *Aegilops cylindrica* Host. AEGCY.

Key words: Interference

In winter wheat production regions of the United States, jointed goatgrass is often a major weed problem. Cultural controls are only partially successful and tend only to suppress the weed (Donald and Ogg 1991). In 2001, imazamox, the first herbicide labeled for selective control of jointed goatgrass in wheat, was registered (Anonymous 2001). This herbicide, however, can be used only with herbicide tolerant CLEARFIELD™ wheat. Thus, this new control option may prove relatively expensive and through hybridization may lead to acetolactate synthase (ALS) resistance in jointed goatgrass (Seedfeldt et al. 1998). Therefore, there is still a need to continue researching alternative control methods.

In Nebraska, competitive ability of wheat cultivars was attributed to high grain yields and greater mature (Zadocks 91) height (Wicks et al. 1986). Among ten winter wheat cultivars, stepwise regression analysis revealed that wheat height when the flag leaf was present (Zadocks 37) was better correlated to downy brome (*Bromus tectorum* L.) yield suppression than canopy diameter or tiller number measured at Zadocks 37 (Cahallaiah 1986). Among seven spring barley cultivars, competitiveness was considered a dynamic trait unidentifiable by measurements of photosynthetically active radiation (PAR) at the soil surface at either of two dates (Christensen 1995). In Australia, the most competitive wheat genotypes against rigid ryegrass established profuse amounts of early biomass, had high tiller numbers, and were tall, with extensive leaf display and shading ability (Lemerle et al. 1996). Among 16 spring wheat genotypes competing against cultivated oat and oriental mustard (*Brassica juncea* L.), those that were taller when the flag leaf was present, had early rapid growth, early maturity (days to spike emergence), and horizontal leaf orientation were better competitors (Huel and Hucl 1996).

In Washington state, seven soft white winter wheat cultivars adapted to the Pacific Northwest were studied for their competitiveness against jointed goatgrass. No trait was identified that was critical in reducing the loss of wheat seed production (Ogg and Seefeldt 1999). However, in related research, four near-isogenic lines of soft winter wheat that differed in height were evaluated for competitive ability. The tallest line reduced jointed goatgrass seed production the most and the shortest line reduced seed production the least (Seefeldt et al. 1999).

In addition to growth characteristics affecting competitive ability, allelopathy may affect competitive ability. In experiments using agar plates, 92 wheat cultivars from Australia and 453 world wide wheat accessions were screened for their alleopathic ability against rigid ryegrass (*Lolium rigidium* L.) and differences were found in inhibition of rigid ryegrass root elongation (Wu et al. 2000a, Wu et al. 2000b). Strongly allelopathic wheat accessions exuded more allelochemicals than weakly allelopathic wheats (Wu et al. 2001). Even though allelopathy exists in wheat, scientists have not isolated the chemical(s) responsible nor have they confirmed allelopathic effects on other weeds. Therefore, there is a need to continue researching the agronomic attributes(s) that contribute to the competitive ability of a cultivar.

In previous experiments in Oklahoma, popular hard red winter wheat cultivars varied in their completive ability with jointed goatgrass (J. Roberts, unpublished data). In that work, mature plant height was not the only characteristic that conferred competitive ability in winter wheat. However, because of the limited number of cultivars evaluated, the work could not clearly define characteristics related to competitive ability. Thus, the goals of this research were to compare an expanded array of cultivars to identify a trait or traits associated with competitive ability.

Materials and Methods

Twenty-four winter wheat cultivars (Table 1) were seeded with and without jointed goatgrass in field experiments in three environments in 1999 and two environments in 2000. Wheat was seeded at 67 kg ha^{-1} into 1.5 x 6-m plots using an eight-row cone seeder with 15-cm row spacing. Jointed goatgrass was seeded simultaneously at 34 kg ha^{-1} in the rows with the wheat in appropriate plots, by blending the jointed goatgrass with the wheat seed. The experimental design was a randomized complete block with a 2 by 24 factorial arrangement with jointed goatgrass presence/absence and wheat cultivars as the factors, plus an added check consisting of jointed goatgrass seeded alone. Treatments were replicated six times.

In 1999, the wheat seed used for the experiments was obtained from either a foundation seed source or a seed company. Germination was tested on the seed of 'Scout 66', 'TAM 107', 'TAM 202', and '2163' because they were more than one year old. Germination of 100 seeds, placed on wet paper towels, rolled up, and placed on a counter at room temperature for one week, was 96, 96, 90, 98, and 86 % for the five cultivars, respectively. Wheat seeded in 2000 was saved from plots seeded in 1999. Germination was tested in September, 2000, in the Oklahoma Crop Improvement Association germination chambers set at a constant 21 $\pm$ 2 °C without light. After one week in the chambers, seedlings were counted. Germination (%) ranged from 98 to 100 %.

Prior to harvest in 2000, loose smut (*Ustilago tritici* (Pers.) Rostr.) was observed in some of the plots. To avoid potential grain loss in 2001, all of the seed was treated with difenoconazole at 3 mL kg^{-1} of seed.

In 1999, all experiments were seeded on October 14 $\pm$ 7 days. The soil in 1999-00 was a Teller loam (fine-loamy, mixed, active, thermic Udic Argiustolls) with pH 5.2 and 0.7 % organic matter (O.M.), a Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) with pH 5.8 and 1.4% O.M., and a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argisutolls) with pH 6.3 and 0.9% O.M. at Perkins, Orlando, and Lahoma, respectively.

In 2000, experiments were seeded on October 3, at Chicksasha and on October 31, at Orlando 2. The soil was a Reinach silt loam (coarse-silty, mixed, thermic, Pachic Haplustols) with pH 6.3 and 1.0 OM and a Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) with pH 5.8 and 1.4% O.M. at Chickasha and Orlando. All experiments were fertilized to satisfy a 4000 kg ha^{-1} yield goal.

Agronomic Measurements

Emerged wheat in one m of the two center rows of each plot seeded only with wheat was counted seven to 10 days after seeding in all experiments except Orlando 2 in 2000. Because of slow and erratic emergence at that site caused by cold weather, the wheat was not counted until late in December. Due to cold conditions, the wheat was slow and erratic in emergence, thus, ample time was allowed for stands to establish (Appendix A).

To determine the influence of wheat biomass production prior to initiation of reproductive growth on jointed goatgrass spikelet production, forage was clipped near the soil surface from one m of the two center rows of all plots in February at all environments except Orlando 2 and oven dried at 60 °C. In plots containing jointed goatgrass and wheat, both species were clipped together.

Wheat canopy heights were estimated by measuring 10 randomly selected plants in each plot at the early hollow stem, flag leaf, and at mature growth stages, (Zadocks 32, 37, and 91 respectively), at all locations in 1999-00 (Zadocks et al. 1974). In 2000-01 at Chickasha, wheat heights were recorded when the flag leaf had emerged and at maturity (Zadocks 37 and 91). All height measurements were taken at the top of the canopy, i. e., the flag leaf was not extended to measure to the tip. Jointed goatgrass height was measured at maturity at all environments except Orlando 2. Jointed goatgrass spikes and wheat spikes were counted within two 1/8 m^2 quadrats per plot at all environments except Orlando 2.

Each plot was harvested using a small plot combine. Yields were adjusted to 13.5% moisture. Volume weights were determined from harvested samples. Jointed goatgrass spikelets were hand separated from a 50 g subsample from each plot seeded with jointed goatgrass and wheat, counted, and weighed. From this data, spikelet production was determined.

Plot Maintenance

Chlorpyrifos at 0.56 kg ai ha^{-1} was broadcast to control greenbug (*Schizaphis graminum* (Rondani)) at Lahoma and Orlando. Bromoxynil at 0.28 kg ai ha^{-1}, chlorsulfuraon + metsulfuron (5:1) at 7.3 + 1.5 g ai ha^{-1}, and ¼ % v $v-^{1}$ of nonionic surfactant were broadcast in December 1999, to control henbit (*Lamium amplexicaule* L.). In the spring of 2000, 122 mL ai ha^{-1} of propiconazole was broadcast at Zadocks 37 to minimize foliar diseases. In the fall of 2000, Italian ryegrass (*Lolium multiflorum* L.) was controlled by applying diclofop-methyl at 2 kg ai ha^{-1} at both sites and henbit and hairy vetch (*Vici villosa* L.) were controlled by triasulfuron applied at 15 g ai ha^{-1}.

Statistical Analysis

Data were analyzed using SAS PROC GLM (SAS 1988). Least significant differences (LSD) in mean values were calculated and means were separated at $\alpha = 0.05$. Except when precluded by interactions, data were pooled across environments. Since multiple samples were not recorded for the weight of the wheat used as seed , years were used as replications to determine whether weight of the wheat seeded varied with cultivar. PROC CORR was used to calculate Pearson correlation coefficients between growth measurements, wheat yield, and jointed goatgrass measurements. Correlations were also used to determine whether wheat coleoptile length, based on rank (Watson 1999), influenced emergence.

Relationships between wheat seed weight and seedling emergence and jointed goatgrass spikelet production were examined using linear regression. Additionally, the relationship between the ratio of jointed goatgrass stand density and wheat stand density to jointed goatgrass spikelet production was determined. Table Curve™ was used for regression analysis (Anonymous 1997).

An evaluation of a crop's competitiveness can be measured as the crop's ability to maintain yield when grown in the presence of the weed and/or the crop's ability to suppress the weed's growth (Huel and Hucl 1996). Thus, both wheat yield loss due to jointed goatgrass interference and the reduction in jointed goatgrass spikelet production by each wheat cultivar were determined. These values were then analyzed using PROC GLM and separated by LSD.

Since the environment can significantly interact with cultivars, it is important to consider the environmental influence upon competitive ability (Lu 1995). to compare the competitive ability of cultivars across environments, nonparametric measures for stability of response, based on ranks, provide a viable alternative to parametric measures based on absolute data (Lu 1995). Also, ranks based on nonparametric data are less sensitive to errors of measurement than parametric measurements. The statistical properties and significance for nonparametric measures of stability were discussed by Nasser and Hühn (1987).

The Hühn's statistic evaluates whether cultivars with similar rankings across environments can be classified as stable across the environments, as well as whether cultivars are stable within an environment. This statistical procedure utilizes a two-way table with K genotypes and N environments where the lowest value is assigned a rank of one and the highest a rank of K. To test the null hypothesis that all genotypes share similar stability across environments, the data is standardized and reranked to calculate the $Z_i^{1,2}$ statistic which is summed and compared to the chi-square distribution ($\chi^2_{0.05,df=K}\Sigma$). To test the null hypothesis that cultivar *i* is stable within an environment, the individual Z_i^1 and Z_i^2 statistics are compared to the chi-square distribution ($\chi^2_{0.05,df=K}$). To compute these statistics and the corresponding chi-square distribution SAS PROC MEANS and PROC RANK were utilized (Lu 1995). However, this program did not compute the Z^2 statistic correctly, thus it was hand calculated using the equations published by Lu (1995).

RESULTS AND DISCUSSION

Competitive Ability

The percent change in wheat yield due to jointed goatgrass interference would not pool across the five environments (P = 0.04). Thus, environment had a greater influence on cultivar yield than jointed goatgrass interference. However, the change in wheat yield at Orlando 2 ranged from -45.2 to -13.4 (%) (Table 2). This may be attributed to slow wheat emergence due to cold weather (Appendix A) and slightly higher jointed goatgrass (57 %) emergence. In the other environments, there was no difference among wheat cultivars in yield loss (%) (P = 0.21, 0.33, 0.14, and 0.37). Thus, jointed goatgrass had little effect on the wheat yield in these environments. However, jointed goatgrass did reduce mean wheat yield when averaged across cultivars from 4930, 2640, 2710, 3760,and 2320 to 4690, 2310, 2420, 2680, and 2160 kg ha^{-1} at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins, respectively ($P = <0.0001$, LSD = 117, 111, 103, 102, and 88)

Although jointed goatgrass had minor effects on wheat yield, the wheat cultivars varied widely in their effect on jointed goatgrass spikelet production. At two environments the four wheat cultivars classified as tall (Watson 1999), 'Larned', 'Niobrara, 'Scout 66', and 'Triumph 64' reduced jointed goatgrass spikelet production more than 'Heyne', 'TAM 202' and '2163' which are classified as short or medium short height cultivars (Table 3). All four tall wheats reduced jointed goatgrass spikelet production more than 'Heyne' at all five environments, and 'Scout 66' reduced jointed goatgrass spikelet production more than 'Heyne', 'TAM 202' and '2163' at all five environments (Table 3). Additionally, 'Heyne' permitted more jointed goatgrass spikelet production at all five environments than 'Lockett', 'Longhorn'; 'Tomahawk', and '2137' (Table 3).

The striking difference in ability to reduce jointed goatgrass spikelet production is demonstrated by cluster analysis. By clustering mean jointed goatgrass spikelet production across the five environments, cultivars with similarities are grouped together. The cluster analysis grouped 'Heyne', 'TAM 202', and '2163' together, as well as grouping together 'Scout 66', 'Triumph 64', 'Lockett', and 'Niobrara' (Figure 1), further suggesting that mature height contributes to competitive ability.

Hühn's nonparametric stability statistic indicated that there were no significant differences in rank stability of jointed goatgrass spikelet production among the 24 cultivars grown in five environments, $\Sigma Z_i^1 = 21.34$ and $\Sigma Z_i^2 = 29.91$ ($\chi^2_{0.05,24}\Sigma = 36.42$). Thus, an individual cultivar's relative competitive ability should be expected to be similar across the five environments. Additionally, individual Z_i^1 values (0.01 to 3.76) and individual Z_i^2 values (0 to 5.63) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no single cultivar was more unstable than another within an environment (data not shown). Therefore, the mean rank of the wheat cultivars for jointed goatgrass spikelet production across the five environments is presented in Table 4. Ranks were assigned with one equaling the highest jointed goatgrass spikelet production and 24 equal to the lowest, however, the ranks are a mean, so a rank of 5.6 indicates the cultivar with the highest jointed goatgrass spikelet production and a rank of 17.0 indicates that the cultivar permitted the lowest spikelet production.

There were a few cultivars that were highly competitive at the majority of the environments, such as 'Scout 66'and 'Triumph 64' and some were consistently poor competitors, such as 'Heyne'. Additionally, there were those that were mediocre in competitiveness and still there were others that showed little consistency. With major differences in competitive ability obvious, identification of responsible characteristics was the remaining question.

Wheat Seed Weight Effects

Weight of the wheat seed planted ranged from 24.2 to 36.8 g 1000^{-1} seeds (Table 1). Years as replications revealed no significant effect of year on seed weight (P = 0.24, C.V. 9.9 %) suggesting that seed size is an inherent trait. Even though R^2 values were not high (R^2 = 0.03 to 0.23), regression analysis demonstrated a logical trend of lower seedling density with greater seed weight at four of five environments (Appendix F). At the fifth environment, (Orlando 2) seedling density increased with increasing seed weight, which was attributed to the cold moist environmental conditions following seeding, with subsequent erratic and prolonged emergence over two months (Appendix A). However, percent emergence demonstrated an increasing trend with increasing seed weight at four of five locations, (R^2 = 0.01 to 0.44) (Appendix G). These results seem to agree with Stockton et al (1996), who found that emergence of hard red winter wheat in Oklahoma decreased when seed weight was lower than 20 g 1000 seeds^{-1}.

Wheat seed weight had little or no effect on jointed goatgrass spikelet production (R^2 = 0.01 to 0.09) (Appendix H). Additionally, wheat seed weight had no correlation to jointed goatgrass height or spike density at any environment, and was variably correlated to jointed goatgrass spikelet production at three of five environments (r = -0.17, -0.25, and 0.16) (P = 0.05, 0.002, and 0.05). Wheat seed weight was negatively correlated to jointed goatgrass spikelets only at Chickasha (r = -0.22, P = 0.008). With no or variable correlation to jointed goatgrass attributes and no linear relationship to jointed goatgrass spikelet production, wheat seed weight was not a significant factor in competitive ability.

Effect of Wheat Stand Density on Competitive Ability

The large differences in stand among wheat cultivars was not expected. When it was detected, the immediate concern was that it would mask other attributes that contribute to competitive ability. Wheat stand density would not pool across the five environments (P = 0.0001), however it would pool across Lahoma, Orlando 1, and Perkins (all seeded in 1999), with a range from 64 to 180 plants m^{-2} (Table 1). Seedbeds at these three environments were cloddy with high levels of crop residue near the surface and moisture was marginal for stand establishment.

At Chickasha and Orlando 2, seedbed conditions were better, however after seeding, the environment became unfavorable. Following seeding at Chickasha, the temperatures were unusually warmer, with high temperatures exceeding 32 °C. Seedling density seven days after planting ranged from 37 to 226 plants m^{-2} (Table 1). Differences were attributed to high-temperature germination sensitivity (Krenzer et al. 2003). High temperature sensitivity also affected jointed goatgrass emergence at Chickasha, which was the lowest of all five locations (Table 1).

Wheat emergence at Orlando 2 was slow and erratic due to environmental conditions after seeding (Appendix A), thus stand density was not recorded until two months after planting. At that time cultivar had no detectable effect on stand density (P = 0.73).

Wheat stand density was not correlated to coleoptile length ranking at any of the five environments. Thus, wheat stand density (plants m^{-2}) was not impacted by coleoptile length.

Wheat emergence results were similar when calculated on a percent basis. Wheat emergence (%) would not pool across the five environments (P = <0.0001), but pooled across Lahoma, Orlando 1, and Perkins, with a range in emergence of 19 to 94 % (Table 1). Emergence at Chickasha ranged from 30 to 75 %, with no cultivar effect at Orlando 2 (P = 0.17) (Table 1).

There were no significant differences in stability of stand density rank among the 24 cultivars across the five environments [$\Sigma Z_i^1 = 19.86$ and $\Sigma Z_i^2 = 24.75$ ($\chi^2_{0.05,24}\Sigma$ = 36.42)]. Individual Z_i^1 values (0 to 3.81) and individual Z_i^2 values (0.02 to 9.47) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), thus no cultivar was more unstable in stand density than another within individual environments (data not shown). Since there was no instability either across environments or within an environment, stand density ranking was not impacted by environment.

Wheat stand density was not correlated to jointed goatgrass mature height at two of four environments (Table 5). At one environment it was negatively correlated, and at another environment it was positively correlated, indicating that wheat stand density was not a controlling factor influencing jointed goatgrass mature height.

At two of four environments, wheat stand density was negatively correlated to jointed goatgrass spike density (Table 5), indicating that a more dense stand may reduce jointed goatgrass spike density.

Wheat stand density was also negatively correlated to jointed goatgrass spikelet production at Orlando 1 and Perkins (Table 5) demonstrating that a profuse stand may decrease jointed goatgrass spikelet production. These environments had good seedbed and emergence conditions, unlike Lahoma, where there was no starter fertilizer or at Orlando 2, where cold weather delayed emergence. Additionally, at Chickasha, there was variable emergence.

At four of the five environments, wheat stand density was negatively correlated to jointed goatgrass spikelet density (Table 5), indicating a dense wheat stand does decrease jointed goatgrass spikelet density. These results concur with the results of Ogg and Seefeldt (1999), who determined that jointed goatgrass seed production was reduced when the wheat stand was thick.

Regression analysis was used to examine the relationship between the jointed goatgrass stand density to wheat density ratio and jointed goatgrass spikelet production. At Perkins and Orlando 1, there was a relationship between the two ($R^2 = 0.34$ and 0.55) (Figure 2).

However, there was no relationship at Chickasha, Lahoma, and Orlando 2 (R^2 = 0.03, 0.07, and 0.01) (Figure 1). The variability in the relationship may be attributed to a lower jointed goatgrass density at Chickasha, poor emergence conditions at Lahoma with no starter fertilizer, and cool temperatures after seeding at Orlando 2.

Rankings for wheat stand density were stable across environments and no cultivar was more unstable within an environment compared to the others, indicating that wheat stand density was not unduly influenced by the emergence conditions at any one environment. Thus, rather than differences in emergence being considered experimental error, they appear to be an inherent trait of a cultivar. Wheat stand density appears to be an important characteristic in reducing jointed goatgrass spikelet production. This agrees with Wicks et al. (1986) that stand density has an influence on competitive ability, however, in their research wheat stand was rated approximately five months after seeding.

Effects of Cultivar Vegetative Growth on Jointed Goatgrass Growth

Forage production of the 24 cultivars would not pool across the four environments sampled (P = <0.0001) and would not pool across environments seeded the first year (P= <0.0001). However, forage production would pool across Chickasha and Orlando 1 with a range among cultivars of 1150 to 1850 kg ha^{-1} (P = 0.59). Forage production of the 24 wheat cultivars grown without jointed goatgrass ranged from 380 to 1350 and 1450 to 3100 at Lahoma and Perkins, respectively (Appendix B).

Forage from cultivars grown without jointed goatgrass was positively correlated with jointed goatgrass mature height at Lahoma. Forage yield was negatively correlated to jointed goatgrass spike density at Lahoma and was negatively correlated to jointed goatgrass spikelet density at Perkins. Additionally, wheat forage yield was negatively correlated to jointed goatgrass spikelet production at Perkins and Lahoma (Table 5).

There was no significant difference in rank stability of forage yield of wheat grown without jointed goatgrass among the 24 cultivars across the four environments ΣZ_i^1 = 33.63 and ΣZ_i^2 = 34.99 ($\chi^2_{0.05,24}\Sigma$ = 36.42). Individual Z_i^1 values (0.01 to 5.35) and individual Z_i^2 values (0 to 3.88) did not exceed the chi-square statistic ($\chi^2_{0.05,24}$ = 9.47), indicating that no cultivar was more unstable than another within an environment (data not shown).

Even though wheat forage yield appears to be stable across environments, it had a limited impact on competition with jointed goatgrass. Ogg and Seefeldt (1999) concluded that cultivars with more biomass may be able to reduce jointed goatgrass seed production, however, it is unclear whether they separated the jointed goatgrass biomass from the wheat biomass.

Effect of Wheat height on Competitive Ability

Wheat Height at Zadocks 32

Height of the 24 cultivars at Zadocks 32 ranged from 23 to 35 cm, 12 to 21 cm, and 8 to 21 cm at Lahoma, Orlando 1, and Perkins, respectively, and was influenced by the three environments sampled (P = < 0.0001) (Table 6). Averaged over cultivars, jointed goatgrass reduced mean wheat height from 17 to 15 cm at Orlando 1 (P = <0.0001, LSD = 0.5), but did not affect height at any other location (P = 0.37 and 0.30). Wheat height at Zadocks 32 at Lahoma was positively correlated to jointed goatgrass mature height

(Table 5). Wheat height at Zadocks 32 was negatively correlated to jointed goatgrass spikelet density, and jointed goatgrass spike yield at Perkins, and was negatively correlated to jointed goatgrass spike density at Lahoma and Perkins (Table 5).

Even though the raw wheat height data measured at Zadocks 32 would not pool across environments, the three environments did not affect the rank stability of wheat height measured at Zadocks 32 among 24 cultivars grown in three environments [$\Sigma Z_i^1 = 29.89$ and $\Sigma Z_i^2 = 33.10$ ($\chi^2_{0.05,24}\Sigma = 36.42$)]. Individual Z_i^1 values (0.04 to 4.21) and individual Z_i^2 values (0 to 4.22) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no cultivar was more unstable than another within an environment (data not shown).

Wheat Height at Zadocks 37

Wheat height did not pool across the four environments sampled (P = <0.001) or the three environments seeded the first year (P = <0.0001). Height ranged from 52 to75, 54 to 76, 46 to 68, and 48 to 63 at Chickasha, Lahoma, Orlando 1, and Perkins, respectively (Table 6). Averaged over cultivars, jointed goatgrass interference reduced mean wheat height at Orlando 1 and Perkins from 56 cm at both locations, to 54 and 55 cm (P = 0.02 and 0.04, LSD =1.8 and 0.8). Wheat height at Zadocks 37 was variably correlated at three of four environments with jointed goatgrass mature height, with one environment positively correlated and the other two negatively correlated (Table 5). Wheat height at Zadocks 37 was negatively correlated to jointed goatgrass spikelet production, and spikelet density, at three environments and was negatively correlated to spike density at all environments sampled (Table 4).

Rank stability of wheat height at Zadocks 37 did not differ across the four environments ($\Sigma Z_i^1 = 26.10$ and $\Sigma Z_i^2 = 31.72$ ($\chi^2_{0.05,24}\Sigma = 36.42$)). Individual Z_i^1 values (0.004 to 4.58) and individual Z_i^2 values (0.02 to 4.09) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no cultivar was more unstable than another within an environment (data not shown).

Since ranks were stable across environments and were negatively correlated to jointed goatgrass spikelet production, the taller the cultivar was at this growth stage, the greater the ability to reduce jointed goatgrass production. This parallels the findings of Balyan et al. (1991) who demonstrated that plant height 35 days after seeding in December was significant in contributing to competitiveness of winter wheat grown in competition with wild oats (*Avena ludoviciana* L). Also, Ogg and Seefeldt (1999) demonstrated that winter wheat cultivars that grew quickly were more competitive against jointed goatgrass.

Wheat height at Zadocks 91

The four environments sampled effected mature height of the 24 cultivars and mature height was effected by the three environments seeded the first year (P = <0.0001). Final wheat height measured at Zadocks 91 ranged from 91 to 111, 82 to 116, 82 to 120, and 73 to 105 cm at Chickasha, Lahoma, Orlando 1, and Perkins, respectively (Table 6). Mature wheat height was negatively correlated to jointed goatgrass spikelet production and spikelet density at two of four environments, and was negatively correlated to spike density at three of four environments (Table 5).

Environment did not affect the rank stability of wheat height measured at Zadocks 91 among the 24 cultivars grown across four environments [$\Sigma Z_i^1 = 30.53$ and $\Sigma Z_i^2 = 34.78$

($\chi^2_{0.05,24}\Sigma = 36.42$)]. Individual Z_i^1 values (0 to 4.84) and individual Z_i^2 values (0.01 to 4.54) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no cultivar was more unstable in mature height than another, within an environment (data not shown).

Ratio of Mature Wheat Height to Mature Jointed Goatgrass Height

The mature height of jointed goatgrass ranged from 57 to 94 cm at the four environments sampled (Appendix E). To determine whether jointed goatgrass height was influenced by wheat height, the ratio of jointed goatgrass height to wheat height measured at Zadocks 91 was determined. Percent ratios ranged from 0.52 to 0.83, 0.71 to 1.05, 0.65 to 1.08, and 0.78 to 1.05 at Chickasha, Lahoma, Orlando 1, and Perkins, respectively (Table 6). Thus, jointed goatgrass does not always grow to the top of the wheat canopy. It was observed that wheat cultivars with the same mature height did not necessarily have the same ratios. For example, at Lahoma, 'TAM 107' and 'TAM 202' were both 88 cm tall but there was a difference of 0.08 in their ratios (Table 6). Furthermore, cultivars that were classified together as medium in height (Watson 2000) had ratios that ranged from 0.75 to 1.05, demonstrating the diversity in the capacity of similar height cultivars to suppress jointed goatgrass mature height. Additionally, the ratio of jointed goatgrass height to wheat height at Zadocks 91 positively correlated to jointed goatgrass spikelet production at three of the four environments sampled (r = 0.44, 0.44, and 0.57) (P = <0.001 at all three). Thus, when jointed goatgrass is able to grow as tall or taller than the wheat, it can produce more spikelets. Moreover, the positive correlations indicate that cultivars which allowed jointed goatgrass to grow as tall or taller as them were not good competitors.

Effect of Wheat Spike Density on Competitive Ability

Spike density of the 24 wheat cultivars ranged from 327 to 429 spikes m^{-2} at Perkins, and 431 to 593 spikes m^{-2} at Chickasha and would not pool across the four environments sampled or across the three environments seeded the first year (P = <0.0001) (Table 7). Jointed goatgrass affected wheat spikelet density only at Perkins where, averaged across cultivars, jointed goatgrass reduced wheat spike density from 405 to 366 spikes m^{-2} (P= <0.0001). Wheat spike density was pooled across Lahoma and Orlando 1. However, there was a significant interaction between cultivar and jointed goatgrass presence indicating that jointed goatgrass variably influenced reproductive tillering of the 24 wheat cultivars and decreased the spike density of only three (Table 7). Jointed goatgrass did not affect wheat spike production at Chickasha (P = 0.77).

Wheat spike density was negatively correlated to jointed goatgrass spike density at one of four environments and was positively correlated at one other (Table 5). Additionally, wheat spike density was correlated to jointed goatgrass spikelet production at three environments (Table 5).

The four environments sampled did not influence the stability of wheat spike density ranks among 24 cultivars [$\Sigma Z_i^1 = 29.62$ and $\Sigma Z_i^2 = 30.97$ ($\chi^2_{0.05,24}\Sigma = 36.42$)]. Additionally, individual Z_i^1 values (0.01 to 4.53) and individual Z_i^2 values (0.003 to 4.54) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no cultivar was more unstable than another within an environment (data not shown).

Wheat spike density was not implicated as a factor in competitive ability. In the literature the effect of wheat spike density on competitive ability is unclear (Ogg and Seedfelt 1999).

Relationship of Wheat Grain Yield and Competitive Ability

Environment affected the wheat yield of 24 cultivars grown without jointed goatgrass, thus, wheat yield would not pool across the five environments sampled, or the three environments seeded the first year, or the two environments seeded the second year ($P = <0.0001$).

Wheat yield was positively correlated to jointed goatgrass spike density at one of four environments (Table 5). Wheat yield was positively correlated to jointed goatgrass spikelet production and spikelet density at three environments (Table 5). Additionally, wheat yield was positively correlated to jointed goatgrass height at three of four environments (Table 5). The environmental conditions in which all jointed goatgrass attributes were positively correlated provided for high wheat yields. Therefore, when the conditions are apropos for high wheat yields, they are also suitable for good jointed goatgrass yields.

The environments sampled for wheat yield did not effect the stability of the ranks of wheat yield among the 24 cultivars [$\Sigma Z_i^1 = 37.12$ and $\Sigma Z_i^2 = 38.05$ ($\chi^2_{0.05,24}\Sigma = 36.42$)]. However, individual Z_i^1 values (0.01 to 7.48) and individual Z_i^2 values (0.09 to 7.97) did not exceed the chi-square statistic ($\chi^2_{0.05,24} = 9.47$), indicating that no cultivar is more unstable than another within an environment (data not shown). Thus, the individual environments had a greater impact on wheat yield than did the genetics of the cultivar.

Wheat yield was adversely affected by jointed goatgrass yield, however wheat yield may not be a critical factor in competitive ability. The reduction in wheat grain yield from jointed goatgrass in these experiments was comparable to reduction in wheat grain yield due to competition with downy brome (*Bromus tectorum* L.) (Challaiah et al. 1986).

Upon comparison of the Hühn's nonparametric rank for jointed goatgrass spikelet production, wheat stand density, forage, height at Zadocks 32, 37, and 91, and wheat spike density it does not appear that any one wheat attribute is responsible for competitive ability (Table 4). Thus, indicating that competitive ability is attributed to several wheat attributes working together to constitute competitive ability. Wheat stand density, wheat height measured at Zadocks 37, and wheat spike density appear to contribute substantially to competitive ability. The Hühn's statistic demonstrated that all three wheat attributes were stable across environments, and that cultivars were stable within an environment. A dense wheat stand is important in quickly closing the canopy and in competing for nutrients. Wheat height at Zadocks 37 corresponds to a period of rapid growth in late March and early April as spring temperatures warm. Hence wheat that quickly recovers from winter dormancy should have an advantage over the weeds. Additionally, wheat spike density is important to wheat yield and canopy closure. Numerous spikes help to maintain a dense canopy. Thus, these traits act together to create a competitive wheat cultivar.

Effects of Cultivar Stand Density on Cultivar Growth and Yield

Wheat stand density was positively correlated to forage yield of cultivars grown without jointed goatgrass at three of four environments (r = 0.37 to 0.49) (P = <0.001,) (Appendix B). Thus, with a denser stand, more biomass is produced.

Wheat stand density was positively correlated to wheat height at Zadocks 32 at one of three environments (r = 0.63) (P = < 0.001) and positively correlated to wheat height at Zadocks 37 at two of four environments (r = 0.19 and 0.53) (P = 0.025 and <0.001) (Appendix B). Wheat stand density also positively correlated to wheat height at Zadocks 91 at two of four environments (r = 0.20 and 0.46) (P = 0.019 and <0.001) (Appendix B). It appears that a dense wheat stand can contribute to a wheat cultivar's height, however, it does not appear to be a dominant factor across all environments in determining a cultivar's height.

Wheat stand density was variably correlated to wheat spike density at two and four environments (r = -0.20 and 0.35) (P = - 0.017 and <0.001) (Appendix B). The negative correlation may be explained by tillering. A wheat cultivar with low stand density may produce more tillers, thus producing more spikes. Thus, stand density may be unrelated to wheat spike density.

Wheat stand density was correlated to wheat yield at four of the five environments but the effects were quite different (r = -0.22, -0.18, 0.18, and 0.71) (P = 0.008, 0.031, 0.022, and < 0.001) (Appendix B). Wheat stand density does not have a consistent relationship to yield. Chickasha and Orlando 2 were the two environments with the negative correlations, which may be associated to greater tillering due to low stand density. At

Chickasha, the stand density was quite variable and at Orlando 2, the stand density was erratic due to cold temperatures.

Thus, wheat stand density appears to have an influence in forage production, a minor impact on height and spike density of a cultivar, and an inconsistent impact on wheat yield.

Jointed Goatgrass

Jointed goatgrass spike density was affected by the four environments sampled (P = 0.001), but was not affected by the three environments seeded the first year (P = 0.42). Mean spike density ranged from 77 to 215 and ranged from 39 to 170 at Chickasha (Appendix E).

The four environments sampled influenced jointed goatgrass spikelet density (P = <0.0001) as did the three environments seeded the first year or the second year (P = <0.0001 and 0.005). Spikelet density ranged from 326 to 1275, 321 to 1395, and 137 to 596 at Lahoma, Orlando 1, and Perkins respectively (Appendix E). At Chickasha and Orlando 2 spikelet density ranged from 27 to 561 and 2430 to 4779 (Appendix E).

Data analysis and interpretation from this work has established that moderate densities of jointed goatgrass in the sampled Oklahoma environments may not have a significant impact on wheat yield. However, the 24 winter wheat cultivars evaluated had variable impacts on jointed goatgrass growth and reproduction. Hühn's statistic demonstrated, that across the sampled environments, wheat stand density, forage production, wheat height at Zadocks 32, 37, and 91, as well as wheat spike density ranks were stable for the 24 cultivars. Additionally, ranks for wheat stand density, forage production, wheat height at Zadocks 32, 37, and 91, wheat density, and wheat yield within an environment were stable, establishing that the cultivars were not greatly impacted by the environments. Stand density, wheat height at Zadocks 37, and wheat yield had the greatest impact on jointed goatgrass spikelet production. Stand density has been implicated as a crucial factor in competitive ability. In the United Kingdom, research established that winter wheat could suppress wild oats (*Avena fatua* L.) with a dense stand, but when the seedling growth was retarded the wheat's ability to suppress was decreased (Thurston 1962).

Older taller wheat cultivars such as 'Scout 66' and 'Triumph 64' suppressed jointed goatgrass spikelet production more than short or medium short wheat cultivars. Modern Australian wheat cultivars are also less competitive than older cultivars (Lemerle et al. 1996). Thus, the competitive ability of the 24 winter wheat cultivars against jointed goatgrass varied greatly, and appears to be related to wheat stand density, wheat height at Zadocks 37, and wheat grain yield.

Acknowledgements

The Oklahoma Wheat Commission and the National Jointed Goatgrass Steering Committee provided partial funding for this research.

Literature Citation

Anonymous. 1997. Table Curve™ 2D v4.0. SPSS Inc. Chicago IL.

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TABLE 1. Wheat cultivars seeded, seed weight, wheat stand density 7 to 10[a] days after seeding, and wheat emergence (%) pooled across Lahoma, Orlando 1, and Perkins, and at Chickasha and Orlando 2.

	Seed weight				Emergence		
Cultivar[b]	pooled over years	Mean[c]	Ck[d]	Or 2[d]	Mean[c]	Ck	Or 2
	g 1000^{-1}		plants m^{-2}			%	
Agseco 7853	34.6	104	37	81	61	17	39
Betty	27.8	172	156	78	79	62	31
Big Dawg	36.8	103	83	96	60	42	49
Coronado	34.4	115	104	87	67	52	43
Culver	29.9	135	133	76	68	58	33
Custer	31.3	149	93	79	71	43	36
Dominator	28.9	160	159	113	72	70	49
Heyne	29.2	64	101	79	27	41	32
Jagger	28.7	168	99	92	75	44	41
Larned	30.7	104	185	94	57	78	40
Lockett	30.4	147	171	89	75	73	38
Longhorn	32.0	131	41	88	72	19	41
Niobrara	25.3	160	34	93	65	13	35
Ogallala	26.8	150	123	85	63	49	34
Scout 66	31.4	130	181	103	66	81	46
TAM 107	31.7	135	106	90	68	49	41
TAM 202	28.4	98	226	89	43	94	37

Thunderbolt	34.1	124	96	94	72	43	42
Tomahawk	32.6	119	170	102	67	73	44
Tonkawa	32.3	146	100	91	77	50	45
Triumph 64	27.9	141	57	87	56	26	40
2137	28.2	165	52	107	66	25	50
2163	24.2	106	44	85	30	19	37
2174	27.2	180	44	102	74	19	45
AEGCY[d]	36.7	47	13	53	51	14	57
C.V.[e]	9.9	28.3	30.4	28.7	28.5	30.8	29.0
LSD (0.05)[e]	6.2	25	6	NSD[d]	15	17	NSD

[a] Wheat stand was counted two months after seeding at Orlando 2.

[b] All wheat cultivars are hard red winter wheats except that Betty and Heyne are hard white wheats. AEGCY spikelets were obtained from wheat harvested the previous year in Oklahoma.

[c] Pooled over Lahoma, Orlando 1, and Perkins.

[d] Abbreviations: Ck, Chickasha; Or 2, Orlando 2; AEGCY, jointed goatgrass (*Aegilops cylindrica* Host.); NSD, no significant difference.

[e] Jointed goatgrass was not included in the ANOVA.

TABLE 2. Yield of 24 wheat cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins, and wheat yield change (%) due to jointed goatgrass presence at Chickasha, Lahoma, Orlando1, Orlando 2, and Perkins.

Cultivar	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins
	%					kg ha^{-1}				
Agseco 7853	-10.1	8.6	-15.3	-23.6	-6.9	5190	2420	2600	3880	2410
Betty	-5.2	-2.3	-1.4	-31.1	-6.6	5140	2540	2550	4200	2560
Big Dawg	0.6	8.4	-18.7	-27.9	-6.2	5110	2430	2540	4230	2110
Coronado	-6.6	-15.8	-14.1	-45.2	-10.2	5390	2880	2970	3680	2530
Culver	-1.6	-17.6	19.5	-29.0	-8.7	4400	2570	2050	3890	1830
Custer	-4.2	-0.5	-8.8	-27.1	-8.0	5230	2340	3210	3850	2320
Dominator	-0.8	-16.3	3.5	-27.9	-8.2	5190	2910	2880	4030	2460
Heyne	-2.6	-6.5	-10.3	-34.9	-13.4	5040	2360	2230	3900	1830
Jagger	-1.1	-14.4	-16.1	-28.3	-6.4	5320	3550	3340	4090	2990
Larned	3.0	-5.9	-24.2	-19.5	-4.5	4190	2300	2340	3350	1700

Lockett	-8.2	-4.6	-4.0	-21.7	-10.0	4710	3940	3040	3420	2730
Longhorn	-3.4	1.9	9.3	-25.8	-3.8	4620	2310	2390	3540	1830
Niobrara	0.8	-24.7	-0.9	-24.0	-6.4	4380	2970	2560	3670	2460
Ogallala	-5.5	-8.1	-21.7	-27.7	-3.6	4600	2610	3320	3130	2440
Scout 66	2.6	-15.1	-7.6	-13.4	-5.2	3970	2210	2410	3370	1570
TAM 107	-7.4	-18.5	-16.3	-39.5	-7.9	4970	2790	3270	3780	2390
TAM 202	-5.0	-11.2	-12.6	-28.9	7.3	4760	2530	2810	3850	1970
Thunderbolt	-9.7	-17.9	-8.2	-27.0	-17.1	5510	2910	3090	3960	2590
Tomahawk	-6.9	-2.5	-10.1	-27.4	-13.5	5180	2530	2420	3820	2820
Tonkawa	-5.6	-17.3	8.9	-25.9	-4.5	4990	2670	2380	3810	1800
Triumph 64	-6.9	2.3	-0.5	-19.8	-3.2	4700	2250	2290	3530	1880
2137	-4.9	-10.5	2.9	-29.0	0.8	5390	2920	2760	3720	2850
2163	-6.3	-24.8	-18.5	-41.0	-9.9	5100	2200	2790	3750	2860
2174	-7.8	-11.7	-9.6	-29.3	-6.0	5130	3120	2730	3850	2860
LSD (0.05)		NSD[a]		12.5	NSD	360	490	530	370	200

[a] Abbreviations: AEGCY, jointed goatgrass (*Aegilops cylindrica* L.); NSD, no significant differences.

TABLE 3. Effect of wheat cultivar on jointed goatgrass (*Aegilops cylindrica* Host.) spikelet production in five environments.

Wheat	Spikelet production				
cultivar	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins
	kg ha^{-1}				
AEGCY[ab]	780	1090	1070	2300	1030
Agseco 7853	48	105	205	780	88
Betty	31	95	118	1020	30
Big Dawg	10	130	174	960	62
Coronado	27	185	150	1570	65
Culver	52	175	116	860	126
Custer	21	146	122	1080	104
Dominator	6	118	115	960	33
Heyne	61	233	252	1220	219
Jagger	72	102	113	860	60
Larned	5	177	154	640	98
Lockett	19	82	102	690	98
Longhorn	23	139	127	900	86
Niobrara	43	123	85	660	63
Ogallala	102	159	147	920	129
Scout 66	4	136	58	570	76
TAM 107	69	122	169	1060	131
TAM 202	33	230	305	1020	217

Thunderbolt	71	204	190	870	146
Tomahawk	33	133	193	870	119
Tonkawa	34	146	125	880	66
Triumph 64	6	114	104	820	60
2137	27	101	138	910	42
2163	43	340	190	1030	120
2174	64	119	152	770	72
LSD (0.05)	19	42	56	290	33

[a] Abbreviations: AEGCY, jointed goatgrass (*Aegilops cylindrica*).

[b] Jointed goatgrass was not included in the ANOVA.

TABLE 4. Hühn's nonparametric stability rank, 1999-01, for jointed goatgrass (*Aegilops cylindrica* Host.) spikelet production across five environments, wheat stand density across five environments, forage yield from plots without jointed goatgrass across four environments, height of jointed goatgrass free wheat across three, four, and four environments at growth stages 32, 37, and 91, respectively, and wheat spike density from plots without jointed goatgrass across four environments.

	AEGCY[a]			Wheat height[b]			
Cultivar	spikelet production	Stand density	Forage	32	37	91	Wheat spike density
Agseco 7853	15.0[c]	13.8	13.8	13.0	12.0	12.8	12.0
Betty	8.4	12.0	12.3	12.7	12.8	12.8	12.3
Big Dawg	10.4	13.2	12.5	14.7	16.0	13.5	12.8
Coronado	5.6	12.2	12.5	11.7	11.8	12.3	11.8
Culver	14.4	11.2	11.0	12.7	12.3	13.8	11.5
Custer	8.2	12.8	13.3	12.7	12.3	12.3	11.8
Dominator	10.4	10.8	12.3	11.7	11.8	13.3	13.5
Heyne	8.0	11.8	12.0	14.3	11.8	12.8	12.0
Jagger	12.4	12.2	12.8	11.7	15.0	12.8	11.0

Larned	17.2	9.8	13.0	14.0	12.0	11.5	12.8
Lockett	16.4	10.2	12.3	12.3	13.8	13.3	14.3
Longhorn	12.0	14.8	12.0	12.0	14.0	13.5	11.3
Niobrara	17.0	16.2	14.3	12.0	10.5	12.0	13.3
Ogallala	12.8	12.4	13.3	14.0	13.0	13.5	13.3
Scout 66	17.8	9.8	12.3	10.7	12.8	11.5	13.5
TAM 107	8.6	12.4	11.0	13.0	10.5	9.8	12.8
TAM 202	13.2	8.2	11.3	12.3	13.3	10.0	13.0
Thunderbolt	14.4	13.6	15.0	12.7	12.3	12.5	9.8
Tomahawk	14.0	10.4	13.3	11.3	12.5	13.0	11.8
Tonkawa	13.2	11.8	13.3	11.3	12.3	12.5	13.5
Triumph 64	14.0	15.0	11.5	11.7	12.5	13.5	13.0
2137	11.0	16.2	13.0	12.0	11.5	12.5	13.5
2163	10.4	14.2	11.5	13.0	13.0	12.8	13.8
2174	15.2	15.0	11.0	12.7	10.8	12.3	12.3

[a] Abbreviations: AECGY, jointed goatgrass (*Aegilops cylindrica*)

[b] Height measured at growth stages indicated using the Zadocks growth scale (Zadocks et al. 1974).

[c] Hühn's nonparametric rank of stability for cultivars across environments (Nasser, R. and M. Hühn 1987). The calculated Z statistics did not exceed the chi-square statistic, thus the cultivars' ranks are stable across environments. A rank of 1 indicates a high value, while a rank of 24 indicates a low value

TABLE 5. Pearson's correlation coefficients of jointed goatgrass (*Aegilops cylindrica* Host.) mature height and yield measures to growth and yield of wheat grown without jointed goatgrass at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins[a].

Jointed goatgrass mature				Wheat height[b]			Wheat	
height and yield measures	Location	Wheat density	Forage	32	37	91	spike density	grain yield
		plants m^{-2}	kg ha^{-1}	cm			spikes m^{-2}	kg ha^{-1}
Mature	Chickasha	-0.21[†]	-0.02	---	-0.45[‡]	-0.07	0.22[‡]	0.37[‡]
height (cm)	Lahoma	0.53[‡]	0.37[‡]	0.59[‡]	0.51[‡]	0.43[‡]	0.36[‡]	0.64[‡]
	Orlando 1	-0.11	0.03	0.04	-0.02	0.14	0.10	0.21
	Perkins	0.08	0.04	-0.16	-0.17[†]	-0.07	-0.02	0.09
Spikes (no. m^{-2})	Chickasha	-0.21[†]	-0.13	---	-0.56[‡]	-0.27[‡]	0.15	0.29[‡]
	Lahoma	-0.02	-0.16	-0.17[†]	-0.33[‡]	-0.34[‡]	-0.20[†]	-0.12
	Orlando 1	-0.05	-0.01	-0.14	-0.17[†]	-0.12	0.00	0.10
	Perkins	-0.42[‡]	-0.38[‡]	-0.22[‡]	-0.22[‡]	-0.22[‡]	-0.09	-0.10
Spikelet production (kg ha^{-1})	Chickasha	-0.13	-0.04	---	-0.57[‡]	-0.21[‡]	0.21[‡]	0.26[‡]
	Lahoma	-0.16	-0.20[†]	-0.10	-0.15	-0.15	-0.18[†]	-0.14

	Orlando 1	-0.22‡	-0.07	-0.16	-0.25‡	-0.12	0.01	0.04
	Orlando 2	-0.07	---	---	---	---	--	0.20†
	Perkins	-0.49‡	-0.23‡	-0.27‡	-0.46‡	-0.46‡	-0.26‡	-0.19†
Spikelets (no. m^{-2})	Chickasha	-0.17†	-0.05	---	-0.59‡	-0.26‡	0.23‡	0.22‡
	Lahoma	-0.09	-0.15	0.01	-0.04	-0.05	-0.09	-0.04
	Orlando 1	-0.19†	-0.09	-0.13	-0.21†	-0.09	0.14	-0.03
	Orlando 2	-0.21‡	---	---	---	---	---	0.29‡
	Perkins	-0.50‡	-0.19†	-0.23‡	-0.43‡	-0.45‡	-0.25‡	-0.17†

[a] Significant at the 0.05 level = † and significant at the 0.01 level = ‡.

[b] Height measured at growth stages indicated using Zadocks growth scale (Zadocks et al. 1974).

TABLE 6. Height of 24 wheat cultivars grown in plots without jointed goatgrass (*Aegilops cylindrica* Host.) at Zadocks 32, 37, and 91 and the ratio of the mature height of jointed goatgrass growing in plots with wheat to height of wheat grown without jointed goatgrass at Zadocks 91 at Chickasha, Lahoma, Orlando 1, and Perkins.

	Chickasha			Lahoma				Orlando 1				Perkins			
Cultivar	37[a]	91	ratio	32	37	91	ratio	32	37	91	ratio	32	37	91	ratio
	cm			cm				cm				cm			
Agseco 7853	57	95	0.80	27	59	96	0.91	16	52	93	0.97	15	55	86	0.87
Betty	54	100	0.73	22	54	91	0.94	14	47	90	0.89	14	51	89	0.89
Big Dawg	66	99	0.75	23	58	91	0.95	17	69	91	0.91	17	64	84	0.89
Coronado	60	93	0.79	34	65	87	1.01	20	54	83	0.91	22	58	82	0.93
Culver	56	99	0.76	27	58	97	0.89	15	49	93	0.89	11	48	79	0.99
Custer	61	96	0.82	29	64	90	0.97	15	57	91	0.94	13	54	83	0.94
Dominator	62	94	0.77	30	62	85	1.04	29	61	86	0.92	22	66	81	0.93
Heyne	50	97	0.81	24	58	92	0.96	16	50	85	0.94	15	50	79	1.00
Jagger	55	97	0.80	37	70	93	1.05	22	58	94	0.94	20	62	86	0.87

Larned	73	108	0.52	26	73	114	0.77	18	64	119	0.76	13	59	91	0.87
Lockett	60	98	0.65	27	65	99	0.91	16	59	96	0.85	11	50	79	0.96
Longhorn	64	100	0.76	32	64	103	0.91	21	61	100	0.84	20	58	83	0.92
Niobrara	53	100	0.74	29	61	102	0.89	15	47	93	0.86	14	50	88	0.91
Ogallala	52	90	0.83	26	53	81	1.05	18	49	87	1.03	15	50	77	1.01
Scout 66	77	110	0.59	30	72	116	0.74	23	71	124	0.65	16	62	91	0.78
TAM 107	59	98	0.77	32	65	88	0.94	18	56	111	1.00	15	58	87	0.93
TAM 202	61	93	0.75	26	59	88	1.02	21	54	102	1.08	14	50	71	1.05
Thunderbolt	51	102	0.77	23	60	94	0.93	11	47	90	0.92	7	45	82	0.95
Tomahawk	57	97	0.82	31	62	91	1.01	16	47	85	0.96	16	53	81	0.98
Tonkawa	63	102	0.74	33	69	95	1.03	17	54	94	0.91	16	62	86	0.91
Triumph 64	71	104	0.63	30	76	116	0.71	16	66	112	0.72	13	63	98	0.76
2137	56	96	0.80	26	59	94	0.98	14	59	86	1.02	14	56	85	0.88
2163	58	92	0.82	24	55	82	1.00	16	51	84	0.92	16	58	83	0.99
2174	57	92	0.79	28	65	92	0.96	16	51	90	1.01	16	55	83	0.94

LSD (0.05)	4	5	0.09	6	7		0.07	3	9	17	0.11	2	4	4	0.05

[a] Wheat height measured at growth stages indicated using Zadocks growth scale (Zadocks et al. 1974)

TABLE 7. Interaction of wheat cultivars and jointed goatgrass (*Aegilops cylindrica* Host) presence on mean wheat spike density pooled across Lahoma and Orlando 1, and effect of cultivar on wheat spike density pooled across jointed goatgrass presence at Chickasha and Perkins.

	Mean[a]		Chickasha	Perkins
Cultivar	No AEGCY[c]	AEGCY	mean[b]	mean[b]
	spikes m^{-2}			
Agseco 7853	340	392	504	387
Betty	312	322	506	400
Big Dawg	385	358	503	388
Coronado	350	306	492	400
Culver	368	343	559	406
Custer	291	312	462	348
Dominator	363	371	516	426
Heyne	317	405	491	327
Jagger	336	386	531	429
Larned	292	305	593	399
Lockett	338	321	451	377
Longhorn	316	309	538	339
Niobrara	376	340	496	424
Ogallala	359	308	536	396
Scout 66	309	369	493	372
TAM 107	272	321	477	388

TAM 202	384	334	550	373
Thunderbolt	310	333	548	367
Tomahawk	342	347	502	391
Tonkawa	302	315	431	397
Triumph 64	345	355	503	345
2137	323	258	470	406
2163	368	341	470	385
2174	337	285	500	389
LSD (0.05)	——— 51 ———		55	44

[a] Pooled over locations Lahoma and Orlando 1.

[b] Wheat spikes were averaged over jointed goatgrass absence/presence.

C Abbreviations: AECGY, jointed goatgrass (*Aegilops cylindrica* L)

FIGURE 1. Cluster grouping of mean spikelet production of jointed goatgrass (*Aegilops cylindrica* Host.) grown in competition with 24 wheat cultivars averaged across Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins.

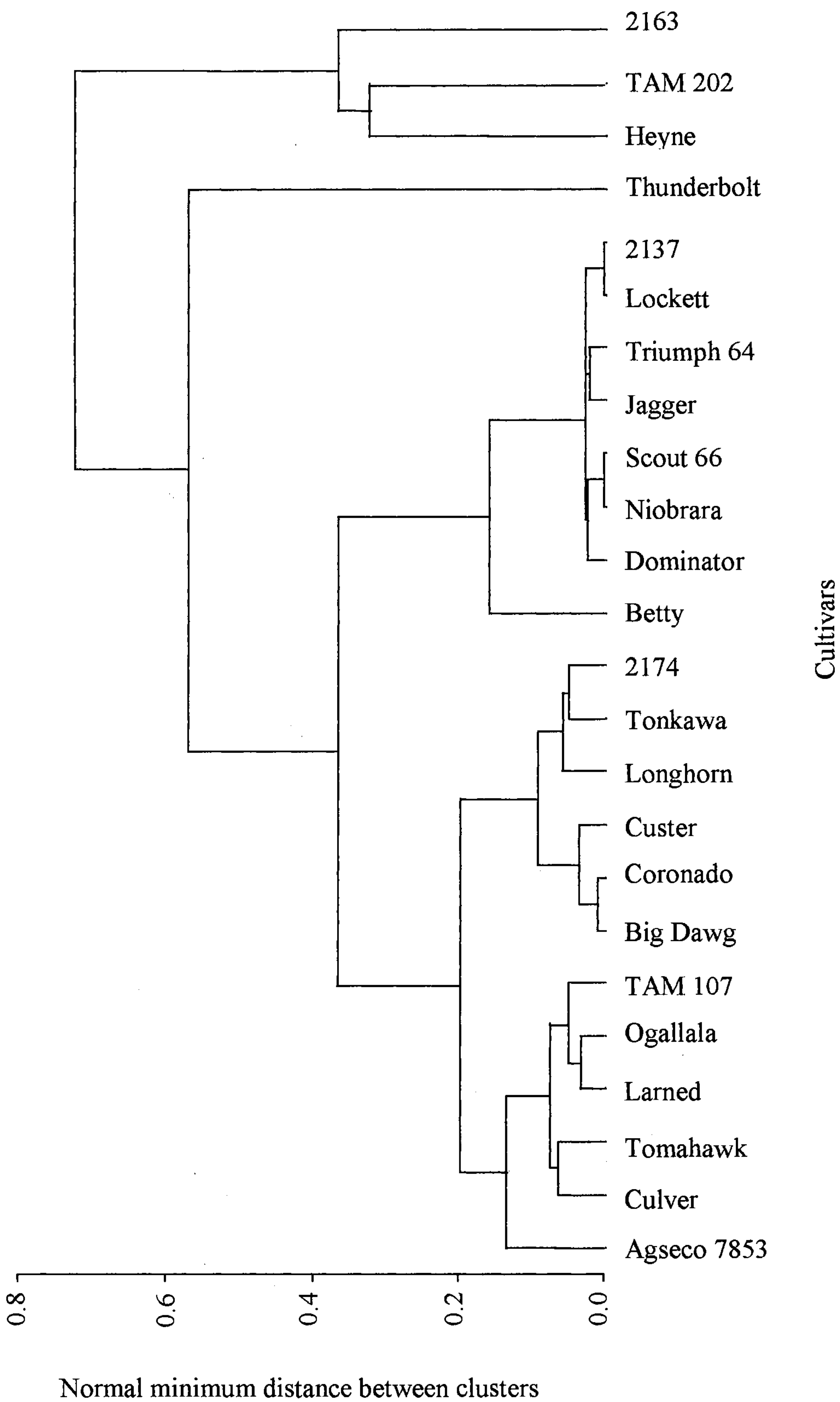
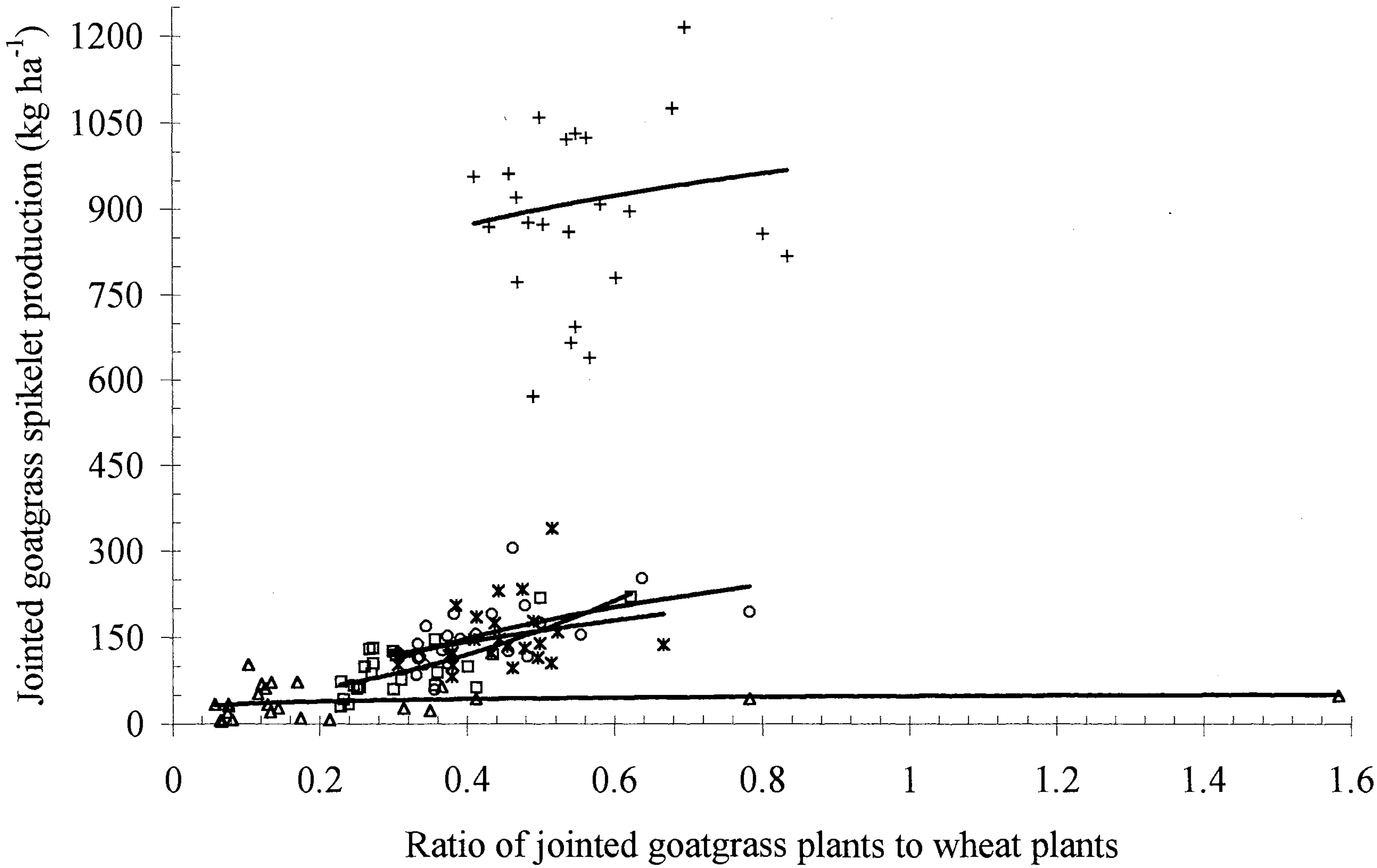

2163
TAM 202
Heyne
Thunderbolt
2137
Lockett
Triumph 64
Jagger
Scout 66
Niobrara
Dominator
Betty
2174
Tonkawa
Longhorn
Custer
Coronado
Big Dawg
TAM 107
Ogallala
Larned
Tomahawk
Culver
Agseco 7853
Cultivars
0.8
0.6
0.4
0.2
0.0
Normal minimum distance between clusters

FIGURE 2. Effect of the ratio of jointed goatgrass (*Aegilops cylindrica* Host.) plants m^{-2} to wheat plants m^{-2} counted 7 to 10 days after seeding (two months after seeding at Orlando 2), on jointed goatgrass spikelet production (kg ha^{-1}) at Chickasha (△): $y = -70.38 + 118.07x^{0.05}$, $R^2 = 0.03$; Lahoma(*): $y = 239.54x^{0.57}$, $R^2 = 0.07$; Orlando 1 (○): $y = -2393.96 + 2665.47x^{0.05}$, $R^2 = 0.34$; Orlando 2 (+): $y = 993.88x^{0.14}$, $R^2 = 0.01$; and Perkins (□) $y = 40.98 + 459.81x^{1.93}$, $R^2 = 0.55$.


Jointed goatgrass spikelet production (kg ha-1)
1200
1050
900
750
600
450
300
150
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Ratio of jointed goatgrass plants to wheat plants

CHAPTER II

REMOTE SENSING TECHNOLOGY TO EVALUATE THE RELATIONSHIP BETWEEN AGRONOMIC CHARACTERISTICS OF WINTER WHEAT (*Triticum aestivum* L.) AND COMPETITIVENESS AGAINST JOINTED GOATGRASS (*Aegilops cylindrica* Host.)

Abstract: To investigate the feasibility of using remote sensing to evaluate variation in competitive ability of winter wheat against jointed goatgrass, an Oklahoma State University (OSU) sensor was used to record incident and reflected wavelengths of 780 and 670 nm from the wheat canopy from which normalized difference vegetative index (NDVI) values were calculated and evaluated as a measure of competitiveness. In replicated field experiments, 24 winter wheat cultivars were grown with and without jointed goatgrass (*Aegilops cylindrica* Host.) at five locations over two years from 1999 to 2001. Data were collected from these experiments weekly except when prevented by inclement weather.

NDVI of the 24 wheat cultivars grown without jointed goatgrass was not useful in estimating mature height of jointed goatgrass grown with the 24 cutivars. However, it was useful in estimating jointed goatgrass spike density, spikelet production, and spikelet density. Several windows of time useful in estimating the ability of the 24 wheat cultivars to suppress jointed goatgrass reproduction. Additionally, it was demonstrated when the morphological characteristics of the 24 wheat cultivars are taken into consideration the correlation between mean NDVI and mean jointed goatgrass spikelet production could be improved from r = –0.25, -0.50, and –0.30 to –0.75, -0.83, and –0.60 when cultivars that do not cover the ground quickly are removed from the data set.

NDVI of the 24 wheat cultivars grown without jointed goatgrass was useful in estimating stand density and forage yield of those cultivars. However, NDVI was unable to consistently estimate wheat height at Zadocks 32, 37, or 91, or wheat spike density, or wheat yield. When stressors such as disease and drought were absent correlations approached 0.9. Classification of the 24 wheat cultivars by published morphological

characteristics greatly improved correlations between NDVI and some wheat attributes. The most consistent estimator of both jointed goatgrass and wheat attributes was the change in NDVI in the fall.

Nomenclature: Winter wheat, *Triticum aestivum* L.; jointed goatgrass, *Aegilops cylindrica* Host. AEGCY.

Key words: Optical sensor, wheat, competition, NDVI

In winter wheat production regions of the United States, jointed goatgrass is often a major weed problem. Cultural controls are ineffective for jointed goatgrass control in wheat (Donald and Ogg 1991). In 2001, imazamox, the first herbicide labeled for control of jointed goatgrass in wheat was registered (Anonymous 2001). This herbicide, however, can be used only with herbicide tolerant CLEARFIELD™ wheat. This new control option may prove relatively expensive and through hybridization may lead to acetolactate synthase (ALS) resistance in jointed goatgrass (Seedfeldt et al. 1998). Therefore, there remains a need to explore alternative weed control methods.

The traditional method of evaluating the competitiveness of a crop against a weed is to physically determine the effect of the weed on crop growth and yield, and/or the affect of the crop on weed growth. In Nebraska, competitiveness in winter wheat cultivars was attributed to high grain yields and greater crop height (Wicks et al. 1986). Among ten winter wheat cultivars, wheat height, when the flag leaf was present (Zadocks 37), was better correlated to downy brome (*Bromus tectorum* L.) yield suppression than canopy diameter or number of tillers m^{-2} present at Zadocks 37 (Challaiah 1986, Zadocks et al. 1974). In Australia, wheat genotypes most competitive against rigid ryegrass established profuse early biomass, had numerous tillers, were tall, and had extensive leaf display and shading ability (Lemerle et al. 1996). Among 16 spring wheat genotypes competing against cultivated oat and oriental mustard (*Brassica juncea* L.), those that were taller at Zadocks 37, had early rapid growth, early maturity (days to spike emergence), and horizontal leaf orientation were better competitors (Huel and Hucl 1996). However, measurements of photosynthetically active radiation (PAR) penetrating the canopy of seven spring barley cultivars at either of two dates was an unsatisfactory method of determining competitiveness (Christensen 1995).

Traditional field methods of evaluating cultivars in breeding programs for competitive ability are expensive in terms of labor, time, and materials (Fehr 1987). Additionally, investigations of crop growth often include repeated and destructive measurements of dry matter, which can be tedious and time consuming (Christensen and Goudriaan 1993). In contrast, measuring spectra reflected from crop canopies at different wavelengths in the photosynthetically active and near-infrared regions can simultaneously, nondestructively, and rapidly estimate traits such as green canopy area and radiation-use efficiency (Field et al. 1994, Penuelas 1998).

Various mathematical combinations of reflectances from the visible band (0.58 to 0.68 μm (red)) and reflectances from the near-infrared (NIR) band (0.73 to 1.10 μm) are sensitive indicators of the presence and condition of green vegetation (Lillesand and Kiefer 1994). Two indices routinely calculated from the reflectance of red and NIR bands are a simple vegetation index [NIR – red] and a normalized difference vegetation index (NDVI) [(NIR – red)/ (NIR + red)], with NIR measured at 780 $\pm$ 5 nm and red measured at 670 $\pm$ 5 nm. (Lillesand and Kiefer 1994). The highest NDVI values are assumed to represent the maximum vegetation "greenness" and are related to several vegetation parameters such as leaf area index, biomass, ground cover, and absorption of sunlight by the canopy (Lillesand and Kiefer 1994). The use of remote sensing and the corresponding indices to discriminate among crop variables was demonstrated using Landsat satellite thematic mapper bands (Ahlrichs and Bauer 1983).

Substantial differences in NDVI were found among 33 cultivars of spring wheat suggesting that NDVI can distinguish between high and low grain yields in cultivar yield trials (Ball and Konzak 1993). Evaluation of two spring wheat cultivars, through the growing season, using a spectroradiometer measuring wavelengths from 400 to 2400 nm, revealed strong relationships between spectral data and relative soil cover ($r^2 = 0.92$), leaf area index ($r^2 = 0.87$), and biomass ($r^2 = 0.84$) (Ahlrichs and Bauer 1983). They determined that due to crop senescence, the best period for assessing the variables was from Zadocks 21 to Zadocks 61. Among 25 winter wheat genotypes, NDVI was highly correlated to seedling vigor and to above ground biomass measured at Zadocks 91 (Myneni and Kanemasu, 1988). Thus, NDVI can be highly correlated to certain crop variables, such as biomass and yield which are related to competitive ability, however, there are no reports of NDVI being used to determine competitive ability of a crop against a weed.

A sensor built by Oklahoma State University, Biosystems and Agricultural Engineering department has successfully discriminated between field bindweed (*Convulvus arvensis* L.) and soil with 98 % or greater accuracy (Criner et al. 1999). Additionally, spectral reflectances were measured from winter wheat and used to calculate NDVI, which was then used to estimate yield (Raun et al. 2001). Wavelengths were recorded on two sample dates while plants were in Zadocks 30, and then used to create the estimated yield. For six of nine experiments sampled in 1998 – 1999, a significant relationship between grain yield and estimated yield was observed ($r^2 = 0.83$) (Raun et al. 2001).

Therefore, the purpose of this research was to determine whether NDVI, calculated from data collected utilizing a sensor constructed by Oklahoma State University's Biosystems and Agricultural Engineers, could be used to predict competitive ability and other agronomic characteristics of 24 winter wheat cultivars.

MATERIALS AND METHODS

Twenty-four winter wheat cultivars were seeded with and without jointed goatgrass in replicated field experiments at three sites in 1999 and two sites in 2000. The wheat was seeded at 67 kg ha^{-1} in 1.2 x 6.1-m plots using an eight-row cone seeder with 15-cm row spacing. Jointed goatgrass was seeded simultaneously with the wheat at 34 kg ha^{-1} in appropriate plots by blending the jointed goatgrass with the wheat seed. The experimental design was a randomized complete block with a 2 by 24 factorial arrangement with jointed goatgrass presence and wheat cultivars as the factors, plus an added check consisting of jointed goatgrass seeded alone. Treatments were replicated six times.

The wheat seeded in 1999 was obtained from either a foundation seed source or a seed company. The wheat seeded in 2000 was saved from the previous year's experiments.

Prior to harvest in 2000, small amounts of loose smut (*Ustilago tritici* (Pers.) Rostr.) were observed in some of the plots. To avoid potential grain loss in 2001, all of the seed planted in 2000 was treated with difenoconazole at 3 mL kg^{-1} of seed.

In 1999, all experiments were seeded on October 14 $\pm$ 7 days. The soil was a Teller loam (fine-loamy, mixed, active, thermic Udic Argiustolls) with pH 5.2 and 0.7 % organic matter (O.M.), a Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) with pH 5.8 and 1.4 % O.M., and a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argisutolls) with pH 6.3 and 0.9 % O.M. at Perkins, Orlando, and Lahoma, respectively, in 1999-00.

In 2000, experiments were seeded on October 17 $\pm$ 14 days. The soil was a Reinach silt loam (coarse-silty, mixed, thermic, Pachic Haplustols) with pH 6.3 and 1.0 % OM and Pulaski fine sandy loam (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents) with pH 5.8 and 1.4 % O.M. at Chickasha and Orlando. All experiments were fertilized as needed to meet a yield goal of 4000 kg ha^{-1}.

Plot Maintenance

Chlorpyrifos at 0.56 kg ai ha^{-1} was broadcast to control greenbug (*Schizaphis graminum* (Rondani)) at Lahoma and Orlando. Bromoxynil at 0.28 kg ai ha^{-1}, chlorsulfuraon + metsulfuron at 7.29 + 1.46 g ai ha^{-1}, and ¼ % v $v\text{-}^{1}$ nonionic surfactant were broadcast in December 1999, to control henbit (*Lamium amplexicaule* L.). At Zadocks 37 in 2000, propiconazole at 122 mL ai ha^{-1} was broadcast to minimize foliar diseases. In the fall of 2000, diclofop-methyl at 2 kg ai ha-1 was broadcast for Italian ryegrass (*Lolium* *multiflorum* L.) control, and triasulfuron at 15 g ai ha-1 was broadcast for henbit (*Lamium amplexicule* L.) and hairy vetch (*Vici villosa* Roth) control at Orlando and Chickasha.

Sensor Measurements

From about two weeks after seeding, NDVI was determined weekly, weather permitting, until the wheat reached Zadocks 91. Using a portable optical sensor, constructed by the Oklahoma State University Biosystems and Agricultural Engineering Department incident and reflected light at 671 $\pm$ 6 nm (red) and 780 $\pm$ 6 nm (NIR) were simultaneously measured from each plot. On occasion when areas of the experiment were too wet, only those replications that were accessible were measured. Measurements were recorded on an interfaced hand held laptop computer. From 25 to 30 measurements were recorded from the 25 by 61 cm field of view as the sensor was carried at 5 km hr^{-1} and 0.75 m $\pm$ 0.05 m above the canopy the length of the plot. A manual switch was used to tag plot ends in the data set.

Reflected light from a barium sulfate coated plate was recorded and used to calculate absolute reflectance (the ratio of light reflected from the plate to incident light) in order to compensate for spectral shifts due to atmospheric moisture, clouds, atmospheric particulates, and sun angle. Even though sampling was conducted on clear days, to compensate for changes in lighting reflectance, correction values were calculated. Amplified gains were manually set within a range of one to 64 to compensate for changes in incident and reflected light intensity.

Data were transferred from the laptop to a desktop computer and imported into a spreadsheet. With the use of a macro program, the data was corrected for absolute reflectance and NDVI was calculated. Only data from the wheat cultivars grown without jointed goatgrass competition was used to calculate NDVI for statistical comparisons.

Agronomic Measurements

Wheat attributes such as wheat stand density, forage yield, wheat height at Zadocks 32, 37, and 91, wheat spike density, and wheat yield were measured. Additionally jointed goatgrass attributes of mature height, spike density, spikelet production, and spikelet density were measured. The procedures for obtaining the data are given in "Competitive ability of 24 winter wheat (*Triticum aestivum* L.) cultivars against jointed goatgrass (*Aegilops cylindirca* Host.)" thesis chapter 1 (Stone 2003). This paper describes the relationships between sensor obtained data and some of the physical agronomic measurements reported for analysis in that paper.

Data Analysis

Data were analyzed using SAS PROC CORR (SAS 1988) to calculate Pearson correlation coefficients between individual NDVI values of each cultivar grown without jointed goatgrass and stand density, biomass production, height at Zadocks 32, 37, and 91, spike density, and yield of jointed goatgrass free wheat. Additionally, Pearson correlation coefficients were calculated between individual NDVI values of cultivars grown without jointed goatgrass, and mature height, spike density, spikelet production, and spike density of jointed goatgrass growing with each wheat cultivar. Since the cultivar competition experimental factors were not paired, the means of NDVI and wheat and jointed goatgrass attributes were also correlated.

Nonlinear regression analysis using Table Curve™ (Anonymous 1997) was used to explore the relationship between fall increase in NDVI with jointed goatgrass spikelet production and spring increase in NDVI with jointed goatgrass spikelet production.

To examine the relationship between NDVI and the relative rate of biomass accumulation, changes in NDVI over time were calculated. The relative biomass accumulation in the fall was estimated as the change in NDVI between 20 $\pm$ 1 DAP and 74 $\pm$ 4 DAP at Lahoma, Orlando 1, and Perkins. The relative biomass accumulation in the spring was estimated as the change in NDVI between 74 $\pm$ 4 DAP and 135 $\pm$ 1 DAP for Lahoma, Orlando 1 and Perkins. NDVI at 144 and 153 DAP and NDVI at 66 and 76 DAP were used to calculate the relative biomass accumulation in the spring at Chickasha and Orlando 2, respectively. The change in fall and spring NDVI were correlated to both jointed goatgrass and winter wheat attributes using PROC CORR.

RESULTS AND DISCUSSION

Jointed Goatgrass Attributes

Individual NDVI Sampling Dates

Individual NDVI correlations to jointed goatgrass attributes were variable and poor to moderate. NDVI of the 24 cultivars grown without jointed goatgrass was positively correlated to jointed goatgrass mature height on 10 of 11 sampling dates at Lahoma (r = 0.24 to 0.68) (Table 1). However, NDVI was negatively correlated to jointed goatgrass height on two of 15 sampling dates at Orlando (r = -0.17 and –0.22), and positively and negatively correlated on two of five sampling dates at Chickasha (r = -0.18 and 0.38) (Table 1). There was no correlation between NDVI and jointed goatgrass height at Perkins (Table 1). The variable correlations indicate that NDVI of the jointed goatgrass free wheat canopy is not a reliable predictor of jointed goatgrass mature height. This would seem reasonable, since early to mid-season NDVI of wheat should be independent of wheat height at maturity.

If NDVI can be related to the ability of a wheat cultivar to suppress jointed goatgrass, it would be a good indicator of competitive ability. NDVIs of the 24 wheat cultivars grown without jointed goatgrass were weakly negatively correlated to jointed goatgrass spike density on nine of 11 sampling dates at Lahoma (r = -0.20 to –0.33) and 13 of 14 sampling dates at Perkins (-0.27 to –0.51) (Table 1). However, NDVI was weakly negatively correlated to spike density on only three of 15 sampling dates at Orlando 1 (r = -0.18, -0.19, and –0.20) and only on one of five sampling dates at Chickasha (r = -0.23) (Table 1). There is an indication that the ability of wheat to limit jointed goatgrass spike density can be assessed by NDVI between 35 $\pm$ 5 and 55 $\pm$ 1 DAP. This window of time corresponds to wheat tillering, specifically reproductive tillering, which is a measure of wheat spike density. Thus, it should be expected that an early sampling time could provide good correlations, but not excellent since not all of the wheat tillers will become reproductive and new tillers will be added in the spring. NDVI from Chickasha was poorly correlated to jointed goatgrass spike density, which may be attributed to the relatively poor establishment of jointed goatgrass (13 plants m^{-2}) at this environment.

NDVI of the wheat grown without jointed goatgrass was weakly to moderately negatively correlated to jointed goatgrass spikelet production on eight of 11 sampling dates at Lahoma (r = -0.19 to –0.41), 11 of 15 sampling dates at Orlando 1 (r = -0.19 to –0.34), one of four sampling dates at Orlando 2 (r = -0.33), and 13 of 14 sampling dates at Perkins (r = -0.26 to –0.55) (Table 1). At Chickasha, NDVI was weakly negatively or positively correlated to jointed goatgrass spikelet production (r = -0.20 and 0.19), which may be attributed to the low jointed goatgrass density. The poor correlations at Orlando 2 may be attributed to the slow and erratic emergence of the wheat and jointed goatgrass that occurred at this location (Stone 2003). There is an indication that the ability of wheat to limit jointed goatgrass spikelet production can be assessed by NDVI between 20 $\pm$ 1 and 85 $\pm$ 1 DAP and between 103 $\pm$ 3 and 109 $\pm$ 5 DAP.

The results were similar for jointed goatgrass spikelet density. NDVI of the cultivars grown without jointed goatgrass was negatively correlated to jointed goatgrass spikelet density on six of 11 sampling dates at Lahoma (r = -0.19 to –0.36), 11 of 15 sampling dates at Orlando 1 (r = -0.18 to –0.34), zero dates at Orlando 2, and 13 of 14 sampling dates at Perkins (r = -0.21 to –0.53) (Table 1). At Chickasha, NDVI correlations were variable (r = -0.19 and 0.16). There appears to be a window of time between 20 $\pm$ 1 and 76 $\pm$ 1 DAP for sampling wavelengths to calculate NDVI for comparing the ability of wheat cultivars to suppress jointed goatgrass spikelet density. These time windows recommended for sampling wavelengths to calculate NDVI correspond to an increase in crop grow in fall as measured by NDVI.

Fall and Spring Changes over Time in NDVI

The positive change in NDVI of the jointed goatgrass free wheat cultivars from selected sample dates was correlated to the jointed goatgrass attributes to determine whether change in NDVI over time could provide a better assessment of wheat's ability to limit jointed goatgrass than NDVI measured at individual sampling dates. Change in NDVI was sampled at three environments in the fall, and at five in the spring.

Fall and spring change in NDVI were variably correlated to jointed goatgrass mature height (r = -0.07 to 0.61) (Table 2). The fall and spring change in NDVI were highly positively correlated to jointed goatgrass height at Lahoma. There was no correlation at the other sites, and supports the conclusion that NDVI should not be used to assess jointed goatgrass mature height.

Fall and spring change in NDVI were negatively correlated to jointed goatgrass spike density at Lahoma and Perkins (r = -0.24 to –0.40) (Table 2). An increase of NDVI in the fall can be used to estimate the relative ability of a wheat cultivar to suppress jointed goatgrass spike density, similar to the individual sampling dates.

Change in NDVI of the jointed goatgrass free wheat in the fall was negatively correlated to jointed goatgrass spikelet production at Lahoma, Orlando 1, and Perkins (r = -0.26 to –0.43) (Table 2). Furthermore, the spring change in NDVI at Orlando 1 and Perkins was positively correlated to jointed goatgrass spikelet density (r = 0.22 to 0.34) (Tale 2). Thus the fall change over time appears to be a better assessor of the ability of wheat to limit jointed goatgrass spikelet production. In addition, unlike the individual NDVI sampling dates, the spring change over time in NDVI may have some potential in assessing potential jointed goatgrass spikelet production.

The fall change in NDVI was negatively correlated to jointed goatgrass spikelet density at Lahoma, Orlando 1, and Perkins (r = -0.18 to –0.39). The spring change in NDVI was positively correlated to spikelet density at Orlando 1 and Perkins (r = 0.22 to 0.34) (Table 2).

The fall change in NDVI appears to be a good assessor of wheats' ability to suppress jointed goatgrass spikelet density, paralleling the window proposed from appraising the individual NDVI sampling dates. Additionally, the correlations between the fall change in NDVI and jointed goatgrass spikelet production support the contention that competitive ability is established early in the growing season.

Regression analysis of the fall change in NDVI with jointed goatgrass spikelet production established negative relationships with a $R^2 = 0.52$, 0.21, and 0.59 at Lahoma, Orlando 1, and Perkins, respectively (Figure 1). With NDVI as a direct measure of biomass, the larger changes in fall biomass of wheat were related to the competitive ability, as measured by limiting jointed goatgrass spikelet production.

Regression analysis of the spring change in NDVI and jointed goatgrass spikelet production established a positive relationship only at Perkins with an R^2 of 0.48 (Figure 2). Thus, cultivars that allowed more jointed goatgrass spikelet production than others had larger changes in NDVI in the spring indicating they grew more in the spring. There was no relationship between the change over time in spring NDVI and jointed goatgrass spikelet production at Chickasha, Lahoma, Orlando 1, or Orlando 2, ($R^2 = 0.04$, 0.04, 0.06, and 0.003, respectively) (Figure 2). With no relationship at four of five environments, the spring change in NDVI was not useful in estimating the ability of the 24 wheat cultivars to suppress jointed goatgrass spikelet production.

Thus, it appears that NDVI recorded in the fall can be used as a measure of competitive ability of winter wheat cultivars against jointed goatgrass. By utilizing the fall change in

NDVI from jointed goatgrass free wheat to indirectly measure the rate of biomass accumulation, relationships can be established to indicate which wheat cultivars are likely to be better competitors with jointed goatgrass than others.

Cultivar Effect on NDVI

Since there were 24 unique winter wheat cultivars with varying ability to compete against goatgrass used in this evaluation (Stone 2003), they may have reduced the correlations between NDVI and jointed goatgrass spikelet production. When the relationship between mean NDVI and jointed goatgrass was examined based on the fall cover capability of the 24 winter wheats, better correlations could be achieved. The 24 winter wheats could be classified into one of three categories based on their ability to quickly cover the ground; "does not cover the ground quickly", "average", or "covers ground quickly" (Watson 1999). When the nine wheat cultivars that do not quickly cover the ground and the three unclassifiable wheat cultivars were removed from the data set, the relationship between mean NDVI and mean jointed goatgrass spikelet production was improved. The correlation between all 24 wheat cultivars and NDVI was r = -0.25, -0.50, and -0.30, and improved to r = -0.75, -0.83, and -0.60 when the cultivars that do no quickly cover the ground and were unclassified were removed from the data set at Lahoma (176 DAP), Orlando 1 (19 DAP), and Orlando 2 (115 DAP) (data not shown).

The improved relationship between mean NDVI and mean jointed goatgrass spikelet production after removal of the cultivars that do not cover the ground quickly parallels findings from the preceding chapter. Experiments comparing competitive ability of the 24 winter wheat cultivars, found that stand was an important characteristic, with cultivars exhibiting a denser stand reducing jointed goatgrass spikelet production. Thus, the cultivars' diverse morphological characteristics have a tremendous influence on the relationship between mean NDVI and mean jointed goatgrass yield. Once the characteristic(s) are accounted for, meaningful relationships can be attained between NDVI and jointed goatgrass spikelet production that can aid in assessing competitive ability of winter wheat cultivars.

Wheat Attributes

Individual NDVI Sampling Dates

Correlation between individual NDVI measurements and wheat attributes varied from to moderately strong. NDVI of the 24 cultivars grown without jointed goatgrass was positively correlated to wheat stand density on two of five sampling dates at Chickasha (r = 0.21 and 0.25), 10 of 11 sampling dates at Lahoma (r = 0.18 to 0.80), 14 of 15 sampling dates at Orlando 1 (r = 0.20 to 0.61), and 14 of 14 sampling dates at Perkins (r = 0.17 to 0.67) with highest correlations occurring early in the growing season (Appendix I). NDVI was negatively correlated to wheat stand density on three of four sampling dates at Orlando 2 (r = -0.20, -0.32, and –0.34). The negative correlations may be attributed to slow and erratic emergence of the wheat and because NDVI was not measured until 76 days after planting. Correlations of NDVI to wheat stand are similar to the findings of Myneni and Kanemasu, (1988), who were able to correlate seedling vigor to NDVI. There appears to be a large window of time (20 $\pm$ 1 and 69 $\pm$ 3 DAP) for using NDVI to assess wheat stand. However, when this window is extended to 109 $\pm$ 5 DAP correlations become variable and include negative correlations. At this growth stage, Zadocks 3, wheat is heavily tillered thus masking individual plants.

NDVI was positively correlated to peak wheat forage production (approximately Zadocks 31) on 10 of 11 sampling dates at Lahoma (r = 0.20 to 0.86), 14 of 15 sampling dates at Orlando 1 (r = 0.22 to 0.41), and 13 of 14 sampling dates at Perkins (r = 0.43 to 0.72) (Appendix I). At Chickasha, NDVI was both positively and negatively correlated on three of five sampling dates (r = -0.22, 0.22, and 0.26). There appears to be two windows of time for using NDVI to assess forage production. The first window is between 20 ± 1 and 85 ± 1 DAP and the second window is between 129 ± 3 and 144 ± 1 DAP. The second window includes the sampling dates on which forage was clipped. Furthermore, the second window includes NDVI from wheat in the last stages of growth. The time between 85 and 139 DAP is associated with mid-winter wheat dormancy,and in 2000 significant snow. The correlation of forage to late season NDVI measurements is comparable to the correlations obtained by Myneni and Kanemasu, (1988) between forage measured at anthesis and NDVI.

NDVI was positively correlated to wheat height at Zadocks 32 on 10 of 11 sampling dates at Lahoma (r = 0.28 to 0.88), 12 of 14 sampling dates at Orlando 1 (r = 0.19 to 0.39, and 12 of 15 sampling dates at Perkins (r = 0.22 to 0.67) (Appendix I). Correlations at Orlando 1 were lower than at the other two environments which was attributed to observed moisture stress. There are two windows for using NDVI to assess wheat height at Zadocks 32, between 47 ± 1 and 85 ±1 DAP, and 129 ± 3 and 144 ± 1.

NDVI on two of five sampling dates at Chickasha (r = 0.19 to 0.34), 10 of 11 sampling dates at Lahoma (r = 0.25 to 0.82), one of 15 sampling dates at Orlando 1 (r = 0.19), and

10 of 14 sampling dates at Perkins (r = 0.18 to 0.36) was positively correlated to wheat height at Zadocks 37. The poor correlation at Orlando 1 may be attributed to late drought stress. There does not appear to be a reliable window of sampling time. There may be a small window of opportunity for sampling between 144 $\pm$ 1 and 156 $\pm$ 4 DAP. However, it does not appear that NDVI is a reliable assessor of wheat height at Zadocks 37, which may be attributed to observing the wheat growing vertically and not accruing more biomass.

NDVI was positively correlated to wheat height at Zadocks 91 on one of five sampling dates at Chickasha (r = 0.27), 10 of 11 sampling dates at Lahoma (r = 0.25 to 0.67), and six of 14 sampling dates at Perkins (r = 0.17 to 0.24) (Appendix I). The poor correlation at Chickasha could be attributed to rains in late May that caused lodging of the wheat. At Orlando 1, NDVI was negatively correlated to wheat height at Zadocks 91 on four of 15 sampling dates (r = -0.17 to –0.19). The poor correlation at Orlando 1 may be attributed to drought stress late in the growing season and the poor correlation at Perkins may be due to differential cultivar response to severe infestations of wheat soilborne mosaic virus (*Polymyxa graminis*) and barley yellow dwarf virus. There was not a reliable window for using NDVI to assess wheat height at Zadocks 91. Therefore, NDVI does not appear to be a reliable assessor of mature wheat height, which should be expected since NDVI is an estimator of biomass and photosynthetic activity and not vertical growth. Myneni and Kanemasu, (1988), also determined that there were no correlation between wheat height at anthesis and normalized difference vegetative index.

NDVI was positively correlated to wheat spike density on 10 of 11 sampling dates at Lahoma (r = 0.25 to 0.81) with only two dates in mid-winter poorly correlated. Two of five sampling dates at Chickasha (r = 0.28 and 0.53), and one of 15 sampling dates at Orlando 1 (r = 0.17). The fact that the sensor consistently predicted wheat spikelet density at Lahoma where growing conditions were good, but did not predict spikelet density at the other sites, where there were conditions interfering with crop growth and yield, indicates that there is potential for using NDVI in the absence of confounding factors. These results conflict in part with the findings of Myneni and Kanemasu, (1988), who determined that there was no relationship between NDVI and wheat spikes m^{-2}.

NDVI was positively correlated, generally strongly, to wheat yield on 10 of 11 sampling dates at Lahoma (r = 0.34 to 0.90), but was weakly correlated to yield at 13 of 15 sampling dates at Orlando 1 (r = 0.17 to 0.34), three of four sampling dates at Orlando 2 (r = 0.16, 0.24, and 0.28), and nine of 14 sampling dates at Perkins (r = 0.16 to 0.25) (Appendix I). At Chickasha, NDVI was negatively correlated to wheat yield on two of five sampling dates (r = -0.21 to –0.29). The negative correlations at Chickasha could be attributed to lodging of some cultivars prior to harvest. There appears to be a window between 129 $\pm$ 3 and 144 $\pm$ 1 DAP for using NDVI to assess wheat yield. Additionally, it appears that sampling on or close to 109 $\pm$ 5 DAP may be useful in assessing wheat yield. Stress factors reducing yield late in the season at four of the five locations adversely affected performance of the sensor. Thus, NDVI may be useful in predicting wheat yield differences among cultivars. Poor correlations between NDVI and wheat yield was attributed to differences in morphological characteristics and susceptibility to diseases, drought and other stresses among the 24 wheat cultivars. These finding agree with Myneni and Kanemasu, (1988), who reported that remotely sensed data by itself could not be used to estimate grain yields of 25 winter wheat cultivars.

Of the five environments, good correlations were found between all wheat characteristics and NDVI only at Lahoma. At Lahoma the wheat grew with very little stress, unlike all other environments. At Lahoma, there were very low levels of wheat soilborne mosaic virus early in the spring, but it quickly disappeared. At Perkins, a heavy infection of wheat soilborne mosiac, as well as barley yellow dwarf virus occurred due to lack of pesticide treatment for aphids in the fall. Also, no soil moisture stress occurred at Lahoma whereas moisture stress was observed for 10 to 14 days in April 2000, at Orlando 1 and Perkins. In 2000-01 Chickasha experienced post-seeding heat stress drying the soil and reducing germination, while Orlando 2 experienced cooler than normal temperatures after seeding causing slow and erratic stand establishment. NDVI is a measure of plant growth and an indicator of stress. Other information is required to separate confounding factors causing plant stress.

The correlation between NDVI values and wheat and jointed goatgrass attributes were sporadic and weak to moderately significant. Some of the individual dates that had no correlation were days with some cloud cover. Individual NDVI values were greatly impacted at each location by factors that were unpredictable. At Chickasha, emergence of some wheat cultivars was affected early by higher than normal temperatures several days after seeding. Lahoma did not receive any starter fertilizer and Orlando 1 experienced slight disease pressure and drought stress in early spring. Orlando 2 had an erratic wheat stand and Perkins experienced disease pressure throughout the spring. The high correlations at Lahoma indicate that the nitrogen stress did not confound the sensor measurements. This was not the case at the other locations.

Cultivar Effect on NDVI

In addition to the pressure placed upon the cultivars from diseases and abnormal environmental conditions, the 24 unique cultivars evaluated greatly influenced NDVI values. When the established characteristics based on the groupings from Watson (1999) were used to group cultivars and these groups used to classify cultivars by expected performance, higher correlations were achieved. When the wheat cultivars were grouped by their fall cover capability and cultivars that did not cover ground removed, correlation between mean NDVI and mean wheat stand at Orlando 2 increased from $r = 0.05$ to $r = 0.45$ (data not shown).

When wheat cultivars were grouped by mature height; and groups classified as medium tall, and tall wheat were removed, correlation between mean NDVI and mean wheat height at Zadocks 37 increased from 0.54 to 0.82 at Perkins (data not shown).

When mean wheat yield was correlated to mean NDVI based on wheat yield potential, correlations were improved. At Orlando 1 the NDVI at 61 DAP, $r = 0.51$ when all cultivars were correlated to NDVI, but the correlation increased to 0.70 when the cultivars classified as having good yield potential (Watson 1999) were removed (data not shown).

It is clear that NDVI can correlate to both jointed goatgrass and wheat attributes, however, the question is whether it is a better estimator of competitive ability than wheat attributes? Of 200 possible correlations between NDVI and jointed goatgrass attributes, 47% were significant at $\alpha = 0.01$ level and an additional 9.5 % at the $\alpha = 0.05$ level. Of 114 possible correlations between jointed goatgrass and wheat attributes, 38.5 % were significant at $\alpha = 0.01$ level and 13 % at the $\alpha = 0.05$ level (data not shown). Neither

NDVI nor wheat attributes correlated more than 55 % to jointed goatgrass attributes. However, NDVI had a higher statistical level of correlation than wheat attributes. Thus, it appears that NDVI is a better assessor of jointed goatgrass attributes than individual wheat attributes.

NDVI can be used to evaluate competitive ability and certain agronomic wheat attributes, such as emergence, forage, and wheat yield. NDVI is a better discriminator than individual agronomic measurements for predicting potential wheat candidates for wheat stand density, forage yield, and competitive ability. However, it is not useful for estimating wheat height at Zadocks 32, 37, or 91, nor is it useful for estimating wheat spike density. Fall and spring changes in NDVI, are better measures of competitive ability of cultivars and better at predicting trends in competitive ability than individual NDVI values. The fall change in NDVI was the best estimator of competitive ability. Optical sensor predictions of measures of competitive ability can be greatly improved if wheat cultivars can be first classified by morphological characteristics such as the rate of ground coverage and relative mature wheat height. Therefore, there is potential for the use of remotely sensed data to aid in estimating and identify competitive cultivars in conjunction with certain agronomic wheat attributes. However, care must be taken to control confounding factors such as disease and drought and to properly classify wheat cultivars.

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TABLE 1. Pearson correlation coefficients between NDVI of 24 cultivars at several dates growing under jointed goatgrass (*Aegilops cylindrica* Host.) free conditions with mature height, spike density, spikelet production, and spikelet density of jointed goatgrass grown with each of the 24 cultivars at Chickahsa, Lahoma, Orlando 1, Orlando 2, and Perkins.

AEGCY[a]		Date NDVI recorded (days after planting)														
attribute	Site[a]	20±1	35±5	47±1	55±1	69±3	76+1	85±1	90±4	103±3	109±5	120+1	129±3	135±3	144±1	156±4
Mature height	Ck	---	---	---	---	0.01[b]	---	---	---	---	---	0.38[‡c]	-0.11	---	-0.17	-0.18[†]
(cm)	La	0.54[‡]	0.41[‡]	0.54[‡]	0.55[‡]	0.62[‡]	0.62[‡]	0.55[‡]	---	0.04	0.24[‡]	---	---	0.68[‡]	---	0.67[‡]
	Or 1	-0.22[‡]	-0.17[†]	0.02	-0.12	-0.13	-0.13	-0.09	-0.15	-0.12	-0.09	-0.10	-0.08	-0.24	-0.07	-0.01
	Pk	0.05	0.03	-0.11	-0.08	0.00	-0.08	-0.03	0.00	0.04	0.08	-0.01	-0.01	-0.01	-0.13	---
Spikes	Ck	---	---	---	---	-0.03	---	---	---	---	---	0.07	-0.07	---	-0.23[†]	-0.09
(no. m^{-2})	La	-0.20[†]	-0.33[‡]	-0.27[‡]	-0.28[‡]	-0.21[†]	-0.20[†]	-0.22[‡]	---	-0.05	-0.02	---	---	-0.25[‡]	---	-0.24[‡]
	Or 1	-0.14	-0.19[†]	-0.15	-0.18[†]	-0.15	-0.15	-0.11	-0.15	-0.20[†]	-0.13	0.02	-0.11	-0.07	-0.05	0.06
	Pk	-0.46[‡]	-0.51[‡]	-0.47[‡]	-0.48[‡]	-0.50[‡]	-0.48[‡]	-0.36[‡]	0.06	-0.39[‡]	-0.28[‡]	-0.27[‡]	-0.35[‡]	-0.37[‡]	-0.33[‡]	---
Spikelet production	Ck	---	---	---	---	0.02	---	---	---	---	---	0.19[†]	-0.02	---	-0.20[†]	-0.07
(kg ha^{-1})	La	-0.29[‡]	-0.41[‡]	-0.33[‡]	-0.35[‡]	-0.29[‡]	-0.31[‡]	-0.22[‡]	---	0.06	0.02	---	---	-0.19[†]	---	-0.14
	Or 1	-0.23[‡]	-0.29[‡]	-0.23[‡]	-0.29[‡]	-0.28[‡]	-0.28[‡]	-0.25[‡]	-0.26[‡]	-0.34[‡]	-0.23[‡]	0.03	-0.19[†]	-0.09	-0.12	-0.04
	Or 2	---	---	---	---	---	0.05	---	0.16	---	-0.33[‡]	---	---	---	---	-0.10

	Pk	-0.38‡	-0.49‡	-0.55‡	-0.47‡	-0.45‡	-0.47‡	-0.37‡	0.09	-0.29‡	-0.32‡	-0.26‡	-0.30‡	-0.29‡	-0.31‡	---
Spikelets	Ck	---	---	---	---	-0.04	---	---	---	---	---	0.16†	-0.02	---	-0.19†	-0.05
(no. m^{-2})	La	-0.22‡	-0.36‡	-0.24‡	-0.27‡	-0.19†	-0.21†	-0.13	---	0.11	0.04	---	---	-0.07	---	-0.02
	Or 1	-0.25‡	-0.31‡	-0.26‡	-0.30‡	-0.28‡	-0.29‡	-0.26‡	-0.25‡	-0.34‡	-0.22‡	0.04	-0.18†	-0.10	-0.09	-0.01
	Or 2	---	---	---	---	---	0.01	---	0.03	---	-0.10	---	---	---	---	0.35
	Pk	-0.37‡	-0.46‡	-0.53‡	-0.43‡	-0.41‡	-0.43‡	-0.34‡	0.08	-0.24‡	-0.28‡	-0.21†	-0.24‡	-0.24‡	-0.25‡	---

[a] Abbreviations: AEGCY, jointed goatgrass (*Aegilops cylindrica*); Ck, Chickasha; La, lahoma; Or 1, Orlando year 1; Or 2, Orlando year 2; Pk, Perkins.

[b] Pearson's correlation coefficient

[c] † = Significant at the 0.05 level and ‡ = significant at the 0.01 level.

TABLE 2. Pearson correlation coefficients between changes in NDVI of jointed goatgrass (*Aegilops cylindrica* Host.) free wheat in the fall (between 74 $\pm$ 4 and 20 $\pm$ 1 DAP[a]) at Lahoma, Orlando 1, and Perkins and in the spring (between 135 $\pm$ 1 and 74 $\pm$ 4 DAP) and jointed goatgrass and wheat attributes at Chickasha[b] Lahoma, Orlando 1, Orlando 2[b], and Perkins.

		Fall			Spring				
Species	Attribute	Lahoma	Orlando 1	Perkins	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins
AEGCY[a]	height at Zadocks 91 (cm)	0.61[c‡d]	-0.11	-0.14	-0.07	0.61[‡]	0.14	---	0.09
	spikes (no. m^{-2})	-0.21[†]	-0.14	-0.40[‡]	-0.12	-0.24[‡]	0.11	---	0.38[‡]
	spikelet production (kg ha^{-1})	-0.28[‡]	-0.26[‡]	-0.43[‡]	-0.12	-0.08	0.21[†]	0.14	0.36[‡]
	spikelets (no. m^{-2})	-0.18[†]	-0.26[‡]	-0.39[‡]	-0.07	0.03	0.22[†]	0.14	0.34[‡]
Wheat	stand (no. m^{-2})	0.71[‡]	0.52[‡]	0.45[‡]	0.12	0.56[‡]	-0.55[‡]	0.07	-0.55[‡]
	biomass (kg ha^{-1})	0.60[‡]	0.36[‡]	0.53[‡]	0.06	0.47[‡]	-0.33[‡]	---	-0.51[‡]
	height at Zadocks 31 (cm)	0.73[‡]	0.32[‡]	0.35[‡]	---	0.85[‡]	-0.14	---	-0.17
	height at Zadocks 37 (cm)	0.68[‡]	0.08	0.25[‡]	0.08	0.78[‡]	0.07	---	-0.08
	height at Zadocks 91 (cm)	0.54[‡]	-0.13	0.25	-0.05	0.64[‡]	0.28[‡]	---	-0.08
	spikes (no. m^{-2})	0.45[‡]	-0.06	-0.03	-0.19[†]	0.48[‡]	0.17	--	0.14

yield (kg ha^{-1})	0.81‡	0.29‡	0.07	-0.04	0.83‡	-0.20†	0.31‡	-0.05

[a] Abbreviations: DAP, days after planting; AEGCY, jointed goatgrass (*Aegilops cylindrica*).

[b] Spring NDVI difference for Chickasha was 144 – 66 DAP, and spring NDVI difference for Orlando 2 was 153 – 76 DAP.

[c] Pearson's correlation coefficient

[d] † = significant at the 0.05 level and ‡ = significant at the 0.01 level.

FIGURE 1. Effect of fall change in NDVI from 24 wheat cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) on jointed goatgrass spikelet production (kg ha^{-1}) at Lahoma (*): $y = 234.41 - 1204.28x$, $R^2 = 0.52$; Orlando 1 (○): $y = 188.60 - 3280.44x^3$, $R^2 = 0.21$; and Perkins. (□): $y = 1155.87 - 1107.75x$, $R^2 = 0.59$.

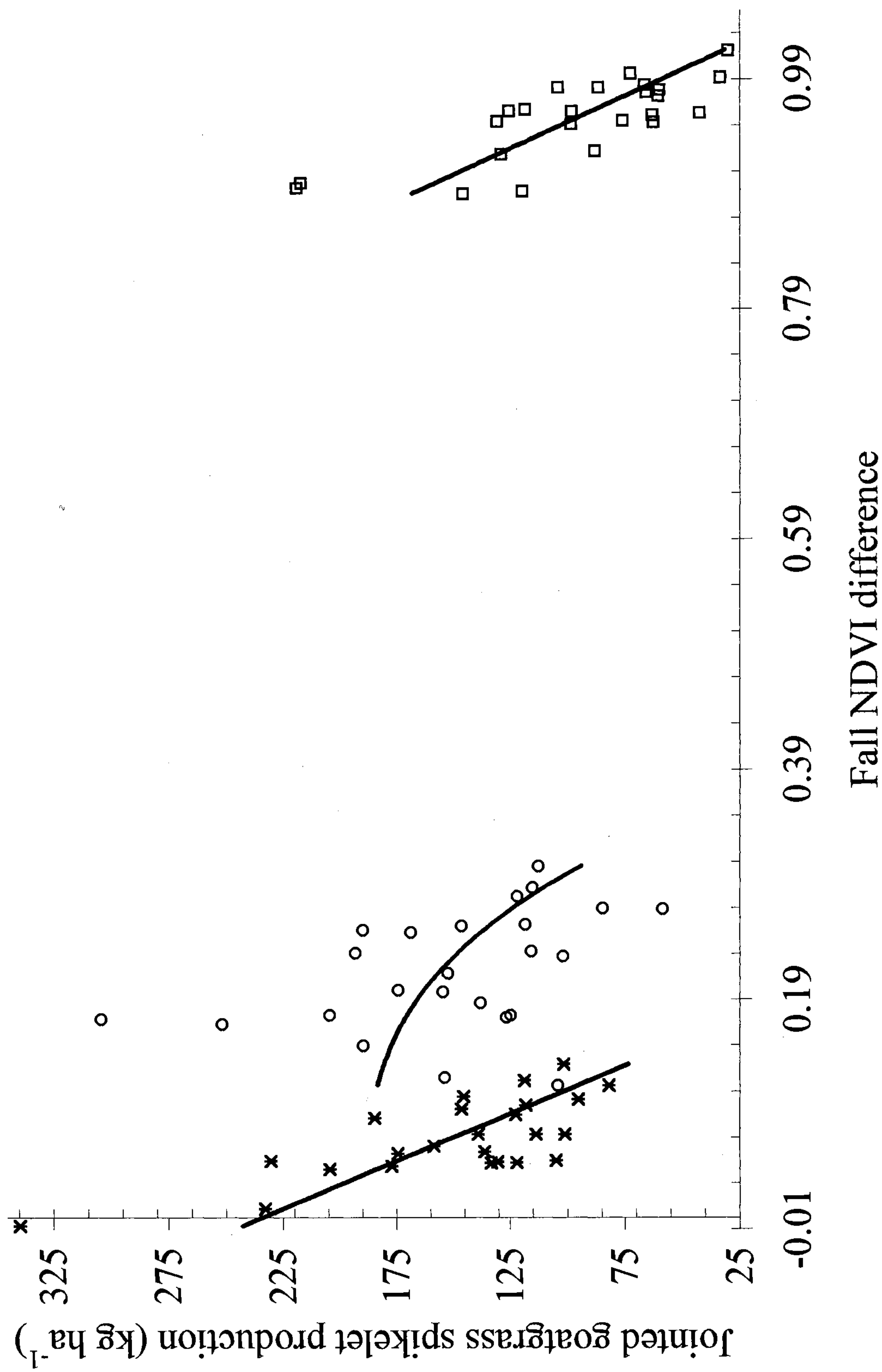
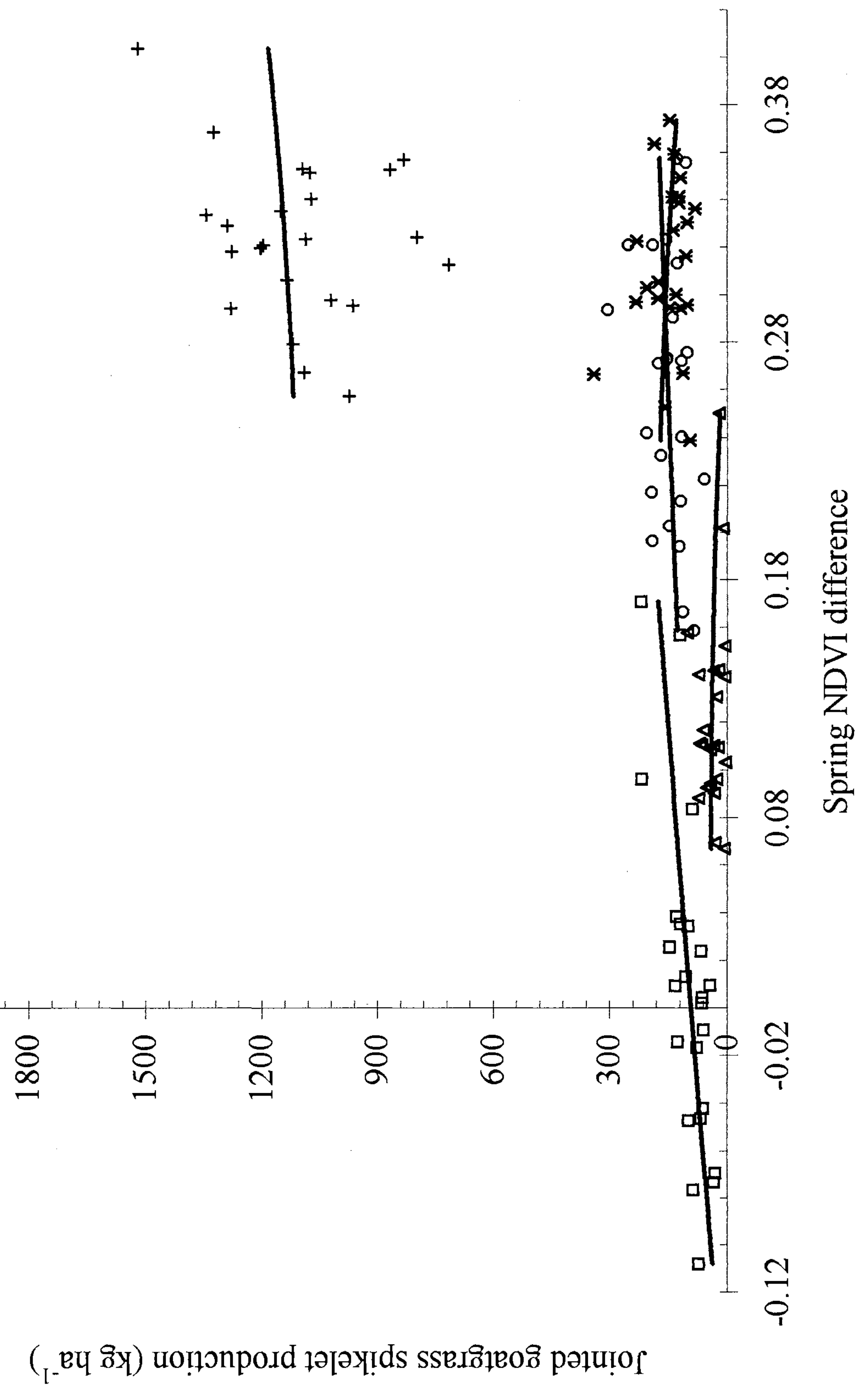

Jointed goatgrass spikelet production (kg ha^{-1})
325
275
225
175
125
75
25
-0.01
0.19
0.39
0.59
0.79
0.99
Fall NDVI difference

FIGURE 2. Effect of spring change in NDVI from 24 wheat cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) on jointed goatgrass spikelet production (kg ha^{-1}) at Chickasha (△): $y = 41.42 - 1510.41x^3$, $R^2 = 0.04$; Lahoma (*): $y = 184.61 - 1070.82x^3$, $R^2 = 0.04$; Orlando 1 (○): $y = 91.00 + 228.43x$, $R^2 = 0.06$; Orlando 2 (+): $y = 1096.09 + 1302.00x^3$, $R^2 = 0.003$; and Perkins. (□): $y = 92.02 + 495.10x$, $R^2 = 0.48$.



Jointed goatgrass spikelet production (kg ha-1)
1800
1500
1200
900
600
300
0
-0.12
-0.02
0.08
0.18
0.28
0.38
Spring NDVI difference

CHAPTER III.

CHARACTERIZING JOINTED GOATGRASS (*Aegilops cylindrica* Host.) - WINTER WHEAT (*Triticum aestivum* L.) HYBRIDS IN OKLAHOMA

Abstract: The introduction of imazamox tolerant winter wheat has increased interest in jointed goatgrass (*Aegilops cylindrica*) – winter wheat (*Triticum aestivum*) hybrids [*Aegilotriticum sancti-andreae* (Degen) Soó] due to the potential for transferring tolerance to jointed goatgrass. Very little is known about such hybrids in Oklahoma, therefore, jointed goatgrass-winter wheat hybrids were identified and harvested for characterization of appearance and germination from 2000 to 2002. Hybrid mature height varied from 46 to 89 cm and spike length varied from 5.0 to 13.8 cm. Hybrid spike color was darker than mature wheat spike color. Mature hybrid spikes disarticulated intact, unlike jointed goatgrass.

Wheat cultivars varied in hybrid production ability. More hybrid plants were produced when jointed goatgrass was grown with 'Dominator' than with several other cultivars. Of 3,338 hybrid spikelets examined in 2000, 0.42 % germinated and produced jointed goatgrass-winter wheat hybrid plants. In 2001, of 16,659 spikelets tested, 166 germinated (0.97 %) and 52 survived to produce spikes in 2002. From the 52 hybrids plants produced in 2002, 7,626 spikelets were collected and 84 (1.10 %) germinated.

Nomenclature: Jointed goatgrass, *Aegilops cylindrica* Host. AEGCY; jointed goatgrass-winter wheat hybrid, [*Aegilotriticum sancti-andreae* (Degen) Soó]; Winter wheat, *Triticum aestivum* L..

Key words: Oklahoma, Southern Great Plains.

Jointed goatgrass and wheat are related by sharing the D genome (Kimber and Sears 1987), and they can cross-pollinate to create hybrids (Dégen 1917). In 1917, the Hungarian, von Dégen, (1917) described and named the hybrid, *Aegilotriticum sancti-andrea*, created by the cross-pollination of jointed goatgrass (*Aegilops cylindrica*) and bread wheat (*Triticum aestivum*). Hybrids can be found world-wide, with confirmed specimens in herbaria in Armenia, Hungary, Iran, Russia, Switzerland, Syria, Turkmenistan, and the United States (van Slageren 1994). There are no specimens in the herbaria at Oklahoma State University or the University of Oklahoma (R. Tyrl; W. Elisens, personnel communications), or at the University of Texas, New Mexico State University, University of Arkansas, University of Nebraska, and Colorado State University (T. Wendt; J. Mygatt; T. Marisco; L. Rader; J. Owens, personnel communications). However, there are approximately 12 specimens in the Kansas State University herbaria (C. Ferguson, personnel communication).

Recent research has established that hybrids may produce seed regardless of the pollen parent and hybrid seed set was similar regardless of pollen donor (Zemetra et al. 1998). Regardless of pollen donor, a low level of female fertility and no male fertility was demonstrated in hybrids. However with a backcross, it was apparent that the pollen donor from the first cross had an influence on restoring female fertility. Plants with jointed goatgrass as the male parent had three times the female fertility of plants with wheat as the male parent (Zemetra et al. 1998). The greater female fertility was found to accompany increases in chromosome homology. Increased chromosome stability occurred in hybrid plants after two backcrosses to jointed goatgrass, indicating that greater female fertility and even self-fertility could be restored with more backcrosses

(Zemetra et al. 1998). Since hybrid plants can increase their female fertility and regain self-fertility, the potential exists to transfer herbicide resistance to jointed goatgrass if the gene of interest is on the D chromosome. It is believed that the gene for imazamox resistance is located on the D genome (Seefeldt et al. 1998).

In Washington state, two hybrid plants were discovered in imazamox-resistant spring wheat that had been replanted from an efficacy trial (Seefeldt et al. 1998). These plants survived treatment with imazamox at 69 g ai ha^{-1}, which was adequate to kill jointed goatgrass. These hybrid plants produced viable seed, which produced plants that demonstrated herbicide resistance (Seefeldt et al. 1998). In field experiments, hybrid plants transplanted into plots containing jointed goatgrass and a soft white wheat produced viable seed (Snyder et al. 2000). Thus in Oregon, jointed goatgrass – winter wheat hybrids backcrossed in a field situation and produced viable seed which germinated and produced plants (Snyder et al. 2000).

Current research to characterize jointed goatgrass-winter wheat hybrids has been centered in the Pacific Northwest. Even though there are hybrid specimens in the central and southern Great Plains, USA, the literature is void of the nature of hybrids in the southern Great Plains. Our objectives were to characterize jointed goatgrass-winter wheat hybrids in Oklahoma and to determine whether hybridizing potential varies among winter wheat cultivars.

MATERIALS AND METHODS

Hybrids initially collected in 2000

Three experiments were planted in central Oklahoma in October 1999, in fields with no prior history of jointed goatgrass, to compare the competitive ability of several winter wheat cultivars with jointed goatgrass. The jointed goatgrass seed used in these experiments was obtained from a grain elevator in Alva, OK, and had been removed from wheat seed delivered by local wheat producers. These experiments contained 24 winter wheat cultivars seeded at 67 kg ha^{-1} into plots 1.2 x 6 m using an eight-row cone seeder with 15-cm row spacing with and without jointed goatgrass. Jointed goatgrass was seeded simultaneously at 34 kg ha^{-1} in the rows with the wheat in appropriate plots, by blending the jointed goatgrass with the wheat seed. The experimental design was a randomized complete block with a 2 by 24 factorial arrangement with jointed goatgrass presence/absence and wheat cultivars as the factors, plus an added check consisting of jointed goatgrass seeded alone. Treatments were replicated six times.

In late May 2000, jointed goatgrass-winter wheat hybrids were identified by appearance in these experiments at all three locations. Mature height of the hybrid plants was measured and mature hybrid spikes were collected before wheat harvest. Each hybrid plant was placed into a labeled paper bag and stored at room temperature until December.

In early December, length of the hybrid spike and number of spikelets on each spike were recorded. Individual spikelets were planted in peat pellets, watered with tap water, and placed on a laboratory bench top at ambient temperatures. Hard red winter wheat cultivar '2163' seed and jointed goatgrass seed were planted in the same manner at the same time. After 10 d, seedlings were transplanted into 15 by 14 cm pots containing potting soil. The pots were placed under growth lights and provided 24 hr of light for one week and then placed into a cold chamber for vernilization at 4.4 °C for 38 d, with 12 hr of light. In late March 2001, all plants were transplanted into a 1 m^2 vegetation free area within wheat field plots, with Teller loam soils (fine-loamy, mixed, thermic, Udic Argiustolls) with pH 5.5 and 0.9 % organic matter (O.M.). The plants were periodically observed for spike emergence and maturation. By mid-June, when hybrid spike emergence had ceased and emerged spikes matured, spikes were collected and placed into labeled bags. Spikelet germination was evaluated in November 2001.

Hybrids initially collected in 2001

In May 2001, hybrids were identified by appearance in three field experiments designed and planted using the same methods as previously mentioned. All experiments were planted in fields with no prior history of jointed goatgrass infestation and the jointed goatgrass seeded was obtained from a wheat elevator in Dacoma, OK, where it had been removed from locally grown wheat. The wheat seed was saved from jointed goatgrass free plots from the previous year's experiments. It was mechanically cleaned and hand picked for purity before seeding. In May and June 2001, hybrid plants were counted in each plot at two locations and were individually collected in June. However, the number of hybrid plants in each plot were not identified and recorded at the third location prior to harvest due to late emergence of spikes, but the plants were collected prior to harvest.

The collected hybrids were stored at room temperature until September, when germination was tested using the Oklahoma Crop Improvement Association's seed laboratory's methods for wheat, i. e. a constant 21 $\pm$ 2 C without light. Spikelets that produced a seedling after one week were transferred to peat pellets, placed under growth lights for a week, and then transplanted to a field with mixed Konowa and Teller soils (fine-loamy, mixed, thermic Ultic Haplustalfs and fine-loamy, mixed, thermic Udic Argiustolls) with pH 5.4 and 0.7 % O.M. to develop tillers.

Chromosomes from apical meristems of 18 of these hybrids plants were affixed following the procedures of Hopkins et al. (1996) and counted. Since apical meristems were required, tillers were removed from each plant without destroying the plants.

Hybrid plants that produced spikes were harvested in June of 2002. Harvesting and germination testing methods were as described previously for 2001, except that hybrid spikelets were placed in a cold room for ten days at 4.4 °C to break potential dormancy prior to germination tests in July 2002.

Statistical Analysis

Hybrid plant densities in each wheat cultivar were analyzed using SAS PROC GLM (SAS) and least significant differences (LSD) in mean values were calculated and separated at $\alpha = 0.05$. Standard deviation and mean were calculated for mature height of hybrids, wheat, and jointed goatgrass; spike length of hybrids, wheat, and jointed goatgrass; chromosome number and spikelet germination from plants selected for chromosome counts. The frequency of viable hybrid plants from the jointed goatgrass seed sources was calculated by counting the hybrid plants m^{-2} in the jointed-goatgrass-only plots and the number of jointed goatgrass plants per m^2 in these same plots.

RESULTS AND DISCUSSION

Characterization of Hybrid Plants

Mature hybrid plants varied in height from 46 to 114 cm ($\bar{x}$ = 76 cm ± 14.8 s.d.). Mature height of the 24 wheat cultivars grown in association with the jointed goatgrass ranged from 55 to 134 cm ($\bar{x}$ = 93 cm ± 11.8 s.d.) and jointed goatgrass mature height ranged from 57 to 93 cm ($\bar{x}$ = 81 cm ± 13.5 s.d.). Hybrid spike length varied from 5.0 to 13.8 cm ($\bar{x}$ = 9.6 ± 1.7 s.d.). Wheat spike length varied from 8.9 to 12.7 cm ($\bar{x}$ = 10.7 ± 1.3 s.d.) and jointed goatgrass spike length varied from 6.4 to 14.0 cm ($\bar{x}$ = 9.8 ± 2.2 s.d.). At maturity, hybrid spikes were darker brown (5 YR 5 / 2) than mature wheat (7.5 YR 7 / 2 to 7.5 YR 6 / 6) (Munsell 1957). In contrast to jointed goatgrass, hybrid spikes typically readily disarticulated intact. Entire spikes were often found on the ground near the parent plant.

The frequency of hybrid plants in the jointed goatgrass seed obtained from Alva, OK was 0.074%. While the frequency of hybrid plants in the jointed goatgrass seed obtained from Dacoma, OK, was 0.078%.

Hybrid Plants

In June 2000, 25 hybrid plants were collected from the three locations. There was no location effect on hybrid density, (P = 0.87). The following June, 346 hybrid plants were collected from the three locations and location again had no effect on hybrid density (P = 0.35) which was expected since the same jointed goatgrass source and wheat source was used at each location within a year.

Hybrid Plants Identified in 2001

In 2000, hybrid plants were collected only from the plots of replicated wheat cultivar competition experiments which contained jointed goatgrass. However, in 2001, hybrid plants were collected from plots which did and did not have jointed goatgrass seeded with the wheat. The number of hybrid plants identified in 2001 pooled across locations, cultivar, and jointed goatgrass presence (P = 0.62). The number of hybrid plants per plot identified was affected by jointed goatgrass presence (P = 0.06). There were 0.41 hybrid plants per 7 m^2 in plots containing wheat and jointed goatgrass and 0.28 hybrid plants per 7 m^2 in plots seeded to wheat without jointed goatgrass (LSD = 0.12). Although the jointed goatgrass seed obtained from Dacoma contained some hybrid spikelets not all of the hybrid plants were from the jointed goatgrass seed. Some were in the wheat seed used for these cultivar competition experiments. The seed that germinated to produce these hybrid plants resembled wheat seed, since the wheat that was planted was carefully cleaned by hand before seed was preweighed into packets for seeding.

Of the 24 wheat cultivars seeded in the fall of 2000, with seed grown near but not with jointed goatgrass, plots seeded with 'Dominator' wheat and no jointed goatgrass had more hybrid plants than plots of any other cultivar (Table 1). Dominator is a hard red winter wheat developed by a private seed company, thus its pedigree is not public information. Differences in anther dimensions and extrusion are well documented in wheat (Atashi-Rang and Lucken1978; De Vries 1973; Khan et al. 1973). Additionally, differences in floret structure could influence the ability of a cultivar to hybridize. This suggests that 'Dominator' or cultivars with similar characteristics may not be good candidates for incorporating herbicide resistance.

Hybrid Spike Production

In 2000, environment in which the cultivar competition experiments were grown influenced the number of spikes produced per hybrid plant. Mean number of spikes per plant was 4.7, 10.8, and 17.7 at Lahoma, Orlando, and Perkins, respectively ($P = 0.053$, $LSD = 9.9$).

In 2001, the environments in which the cultivar competition experiments were grown did not influence mean hybrid spikes per plant ($P = 0.63$, $\bar{x} = 4.0$), which may be attributed to greater uniformity in hybrid plants harvested. There was no difference in mean hybrid spikes per plant in 2002 ($P = 0.11$, $\bar{x} = 13.7$), this may be attributed to similar spike production by the hybrid plants.

Hybrid Spikelets

In 2000, 25 hybrid plants produced 3,338 spikelets and the environment in which they were produced had some influence on production. Mean spikelet production was 58, 137, and 209 spikelets per plant at Lahoma, Orlando, and Perkins, respectively ($P = 0.10$, $LSD = 135$). The location effect can be attributed to the location effect on number of spikes per plant.

In 2001, 16,659 spikelets were harvested from 346 hybrid plants. The mean spikelet production was not influenced by the environment they were produced in ($P = 0.31$).

In 2002, hybrid plants, of which some were second generation and some were further backcrossed, produced 7,626 spikelets. There was not a location effect on mean spikelets per plant ($P = 0.14$). Thus, the generation did not effect spikelet production, nor did the environment.

Hybrid Spikelets per Spike

The number of spikelets per spike (11.9) was consistent across environments in 2000, (P=0.61). In 2001, the mean number of spikelets per spike varied with environment from 11.3, to11.8 (P = 0.09, LSD = 0.04). The difference may be attributable to environmental conditions at each location, but it is uncertain. In 2002, there was no variation in mean spikelet number per spike produced (P = 0.49).

Hybrid Germination and Survival

Of the 3,338 hybrid spikelets collected in June 2000 and tested for viability, 14 produced seedlings (0.42 %). Germination (%) was not influenced by the environment in which the hybrid spikelets were created in (P = 0.16). Of the 16,659 spikelets collected in June 2001 and tested for viability, 166 produced seedlings (0.996 %). Again the environment did not affect the ability of the hybrid spikelets to germinate (%) (P = 0.22). In June 2002, 7,626 spikelets were tested for viability and 84 produced seedlings (1.10 %). Thus, the ability of the hybrid spikelets to germinate was relatively low.

Of the 14 seedlings that emerged in the fall of 2000, 13 survived (0.93 %). Neither survivors nor the wheat and jointed goatgrass transplanted to the field in March produced spikes in the spring of 2001.

Of the 166 seedlings that emerged in 2001, spikes were produced on 52 (0.31 %) in the spring of 2002, 79 died and 35 did not produce normal spikes. The location from which the hybrid spikelets were collected did not effect seedling survival either year (P = 0.48) confirming that hybrid plants can develop across a range of environments.

Differences in Chromosome Number

Chromosome number ranged from 2n = 32 to 53 in the 18 plants in which they were counted (Table 2). This is similar to the findings of Seefeldt et al. (1998) where spring wheat – jointed goatgrass hybrid plants' chromosome numbers ranged from 39 to 54. Since only part of the plant was removed for determination of chromosome number, the remnants of the plant was allowed to mature. Only one of eight hybrid plants with odd chromosomes produced a viable spikelet, while the others either failed to produce spikes or produced no viable spikelets. In contrast 8 of 10 plants with even numbers of chromosomes produced some viable spikelets, though chromosome number did not influence spikelet germination (Table 2). Even though it was observed that even number of chromosomes produced some viable spikelets, there was not statistical difference ($P = 0.16$). The hybrid plant that had 32 chromosomes died (Table 2).

Thus, naturally occurring jointed goatgrass-winter wheat hybrids found in Oklahoma germinated at a rate near 1%. Wheat cultivars differ in their ability to accept jointed goatgrass pollen and create hybrids. Hybrid production was fairly consistent over two years across environments, suggesting that hybridization can be expected to occur over a range of environmental conditions commonly found in Oklahoma wheat fields.

ACKNOWLEDGEMENTS

I would like to thank Dr. Charles Taliaferro and Rose Edwards for the use of their laboratory and assistance in preparing and counting chromosomes.

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TABLE 1. Effect of wheat cultivar seeded into jointed goatgrass (*Aegilops cylindrica* Host.) free plots on the density of hybrid plants identified in wheat cultivar competitive ability experiments, in 2001, pooled across two locations.

Cultivar in which hybrids were found	Jointed goatgrass–wheat hybrids
	—— no. 7 m^{-2} ——
Agseco 7853	0.00
Betty	0.50
Big Dawg	0.67
Coronado	0.08
Culver	0.58
Custer	0.08
Dominator	2.08
Heyne	0.33
Jagger	0.17
Larned	0.33
Lockett	0.08
Longhorn	0.08
Niobrara	0.00
Ogallala	0.00
Scout 66	0.17
TAM 107	0.25
TAM 202	0.33
Thunderbolt	0.08

Tomahawk	0.08
Tonkawa	0.25
Triumph 64	0.17
2137	0.42
2163	0.00
2174	0.17
LSD	0.52
C. V.	221

TABLE 2. Chromosome number of 18 selected hybrid plants, the corresponding number of spikelets that were attempted to germinate, and the number of spikelets that did germinate from those plants in 2002.

Cultivar in which hybrid plant was found	Chromosomes	Attempted spikelets	Spikelets germinated
	no.		
Betty	46	800	25
Coronado	46	217	1
Dominator	32	---	---[a]
Dominator	44	275	8
Dominator	45	110	0
Dominator	47	437	3
Dominator	48	186	2
Dominator	52	276	0
Dominator	52	377	3
Dominator	52	80	4
Dominator	52	40	5

Dominator	53	---	---[b]
Larned	49	162	0
Larned	52	105	0
Larned	53	55	0
Thunderbolt	49	15	0
Thunderbolt	51	12	0
2137	49	---	---[b]
Mean	48	210	3.4
Standard deviation	5.02	208.24	6.43
AEGCY[c]	28	---	---
Winter Wheat	42	---	---

[a] Hybrid plant died.

[b] Hybrid plant did not produce spikes.

[c] Abbreviations: AEGCY; jointed goatgrass (*Aegilops cylindrica*).

Appendix A. 2000 rainfall, and maximum and minimum temperatures at Chickasha and Orlando 2 in October, November, and December and 30 year averages.

			October		November		December	
Location			2000	Historical	2000	Historical	2000	Historical
Chickasha	Rainfall	cm	28	10	8	5	4	5
	Maximum	°C	24	26	12	18	4	12
	Minimum	°C	13	10	1	3	-4	-2
Orlando 2	Rainfall	cm	15	8	6	7	3	4
	Maximum	°C	24	24	12	16	3	10
	Minimum	°C	12	9	0	3	-7	-3

Appendix B. Forage yield removed from two one-m row lengths in February from 24 wheat cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) at Lahoma and Perkins and pooled across Chickasha and Orlando 1.

Cultivar	Lahoma	Perkins	Mean[a]
	kg ha^{-1}		
Agseco 7853	890	1810	1320
Betty	900	2810	1210
Big Dawg	690	2430	1320
Coronado	1060	2670	1550
Culver	770	2280	1510
Custer	700	2430	1620
Dominator	900	2480	1850
Heyne	360	1760	1310
Jagger	770	2510	1370
Larned	600	2040	1190
Lockett	1350	2460	1420
Longhorn	990	2710	1140
Niobrara	960	2400	1520
Ogallala	770	2110	1280
Scout 66	690	2280	1720
TAM 107	740	2190	1660
TAM 202	670	1970	1380

Thunderbolt	760	1450	1520
Tomahawk	600	2410	1290
Tonkawa	1100	2480	1590
Triumph 64	930	2010	1150
2137	910	2360	1430
2163	380	2210	1330
2174	830	3100	1300
LSD (0.05)	380	450	NSD

[a] Pooled across Chickasha and Orlando 1.

Appendix C. Pearson correlation coefficients of wheat attributes at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins.

		Wheat attributes					
				Height[a]			
Site		Stand	Forage	32	37	91	Spikes
		plants m^{-2}	kg ha^{-1}	cm			spikes m^{-2}
Forage	Chickasha	0.14	....				
(kg ha^{-1})	Lahoma	0.49[b‡c]	....				
	Orlando 1	0.37‡	....				
	Perkins	0.37‡	....				
Height - 32	Lahoma	0.63‡	0.52‡	....			
(cm)	Orlando 1	0.00	0.13	....			
	Perkins	0.03	0.39‡	....			
37	Chickasha	0.19[†b]	-0.02	...	....		
(cm)	Lahoma	0.53‡	0.45‡	0.80‡	....		
	Orlando 1	0.05	0.03	0.36‡	....		
	Perkins	0.11	0.16†	0.55‡	....		
91	Chickasha	0.10	0.06	...	0.41‡	....	
(cm)	Lahoma	0.46‡	0.38‡	0.62‡	0.83‡	....	
	Orlando 1	-0.12	0.06	0.31‡	0.27‡	....	
	Perkins	0.20†	0.03	0.04	0.49‡	....	
Spikes	Chickasha	0.04	-0.06	...	-0.06	0.18†	....
(spikes m^{-2})	Lahoma	0.35‡	0.16	0.40‡	0.36‡	0.28‡	....

	Orlando 1	-0.20†	-0.19†	0.06	-0.15	-0.07	....
	Perkins	0.07	-0.11	-0.03	0.04	0.02	....
Yield	Chickasha	-0.18†	-0.02	…	-0.41‡	-0.21†	0.00
(kg ha^{-1})	Lahoma	0.71‡	0.53‡	0.82‡	0.68‡	0.51‡	0.49‡
	Orlando 1	0.13	0.14	0.17	-0.06	0.22	0.10
	Orlando 2	-0.22‡	…	…	…	…	…
	Perkins	0.18†	0.14	0.18†	-0.09	-0.01	0.14

[a] Height measured at growth stages indicated using Zadocks growth scale (Zadocks et al. 1974).

[b] Pearsons correlation coefficient

[c] Significant at the 0.05 level = †, significant at the 0.01 level = ‡.

Appendix D. Range of wheat attributes from Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins.

Wheat attribute	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins
Stand (plants m^{-2})	33 - 226	38 - 177	77 – 152	73 – 97	76 - 217
Stand (%)	12.7 – 93.7	17.9 – 70.5	33.0 – 69.4	30.9 – 50.3	35.4 – 93.3
Forage (kg ha^{-1})	800 – 1790	380 – 1350	1210 – 2080	---	1450 - 3100
Height[a] Zadocks 32 (cm)	---	22 – 37	11 – 29	---	7 – 22
Zadocks 37 (cm)	50 – 77	53 – 76	47 – 69	---	45 - 66
Zadocks 91 (cm)	90 - 110	81 - 116	83 – 124	---	71 – 98
Spikes (no. m^{-2})	441 - 585	252 - 334	319 - 439	---	327 – 429
Yield (kg ha^{-1})	3970 - 5510	2200 - 3940	2050 - 3340	3130 - 4230	1570 - 2990

[a] Height measured at growth stages indicated using Zadocks growth scale (Zadocks et al. 1974).

Appendix E. Jointed goatgrass (*Aegilops cylindrica* Host.) mature height at Chickasha and pooled across Lahoma and Orlando 1; jointed goatgrass spike density at Chickasha and pooled across Lahoma, Orlando 1, and Perkins; and jointed goatgrass spikelet density at Chickasha Lahoma, Orlando 1, Orlando 2, and Perkins.

	Mature height		Spike density		Spikelet density				
Cultivar	Chickasha	Mean[a]	Chickasha	Mean[b]	Chickasha	Lahoma	Orlando 1	Orlando 2	Perkins
	cm		no. m^{-2}		no. m^{-2}				
Agseco 7853	74	93	137	174	270	397	929	2879	386
Betty	72	85	155	101	165	357	543	3346	137
Big Dawg	73	86	84	116	81	489	723	3153	317
Coronado	73	81	117	132	201	683	530	4779	284
Culver	75	82	114	117	348	614	745	3170	568
Custer	80	88	151	128	121	525	548	3504	475
Dominator	72	86	86	103	45	448	537	3108	157
Heyne	77	88	155	192	319	890	1203	4053	906
Jagger	76	94	150	104	419	383	508	3171	268

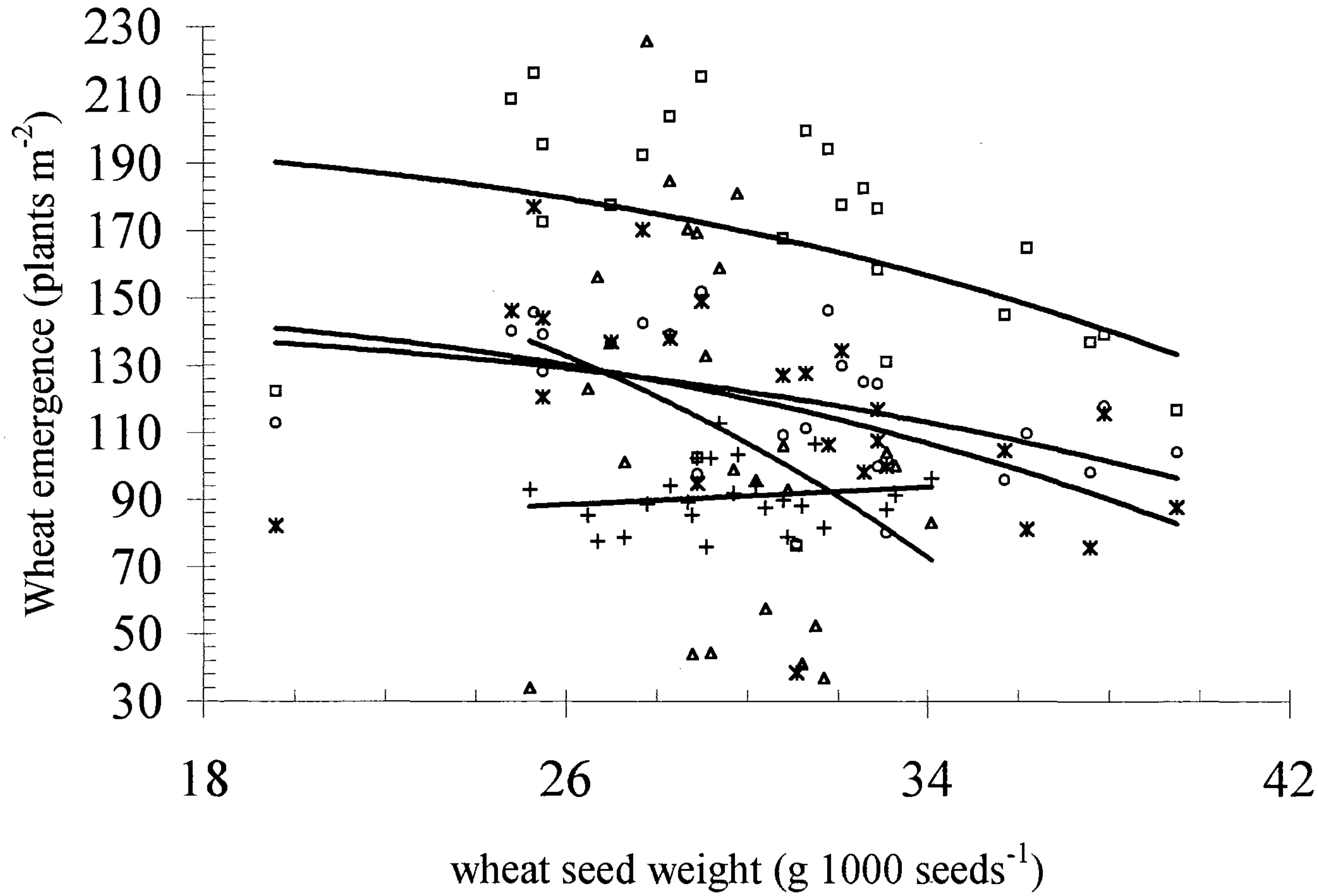
Larned	57	90	81	142	43	704	759	2526	426
Lockett	66	90	75	109	167	326	479	2760	426
Longhorn	75	90	106	112	151	498	592	3239	370
Niobrara	75	81	128	80	267	448	409	2656	273
Ogallala	76	91	152	163	561	618	642	2874	517
Scout 66	64	77	39	77	27	514	321	2430	363
TAM 107	75	88	143	133	382	476	762	3716	596
TAM 202	70	92	99	214	209	837	1395	3340	917
Thunderbolt	79	88	155	180	371	745	802	3202	603
Tomahawk	79	88	120	123	177	496	668	3334	540
Tonkawa	73	90	129	119	222	540	602	2860	296
Triumph 64	65	81	75	104	57	438	526	2818	245
2137	78	93	120	129	183	358	607	3137	201
2163	76	80	132	197	254	1275	933	3345	555
2174	75	92	170	138	365	425	722	2475	352

LSD (0.05)	8	9	44	36	96	169	257	1008	142

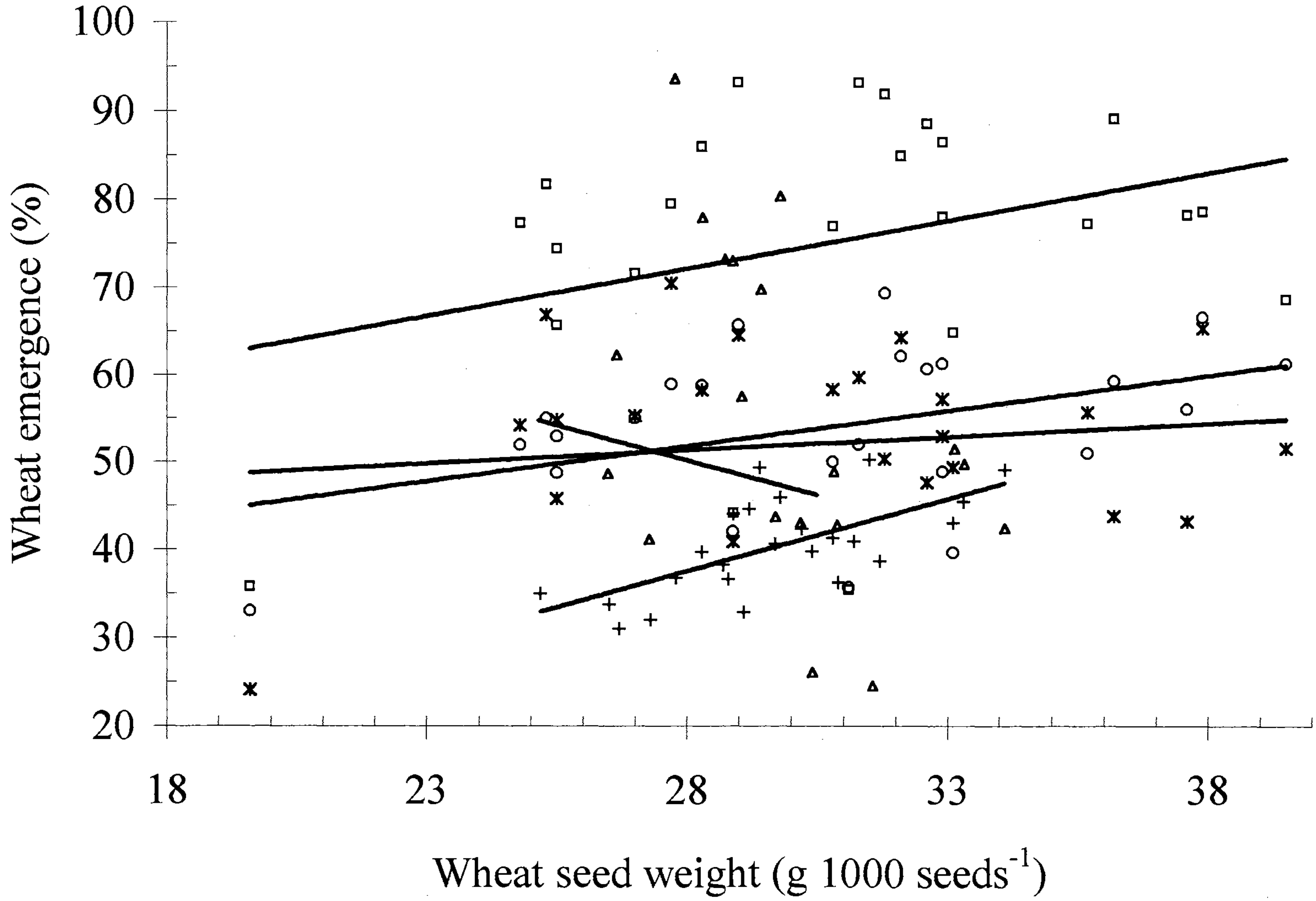
[a] Pooled across Lahoma and Orlando 1.

[b] Pooled across Lahoma, Orlando 1, and Perkins.

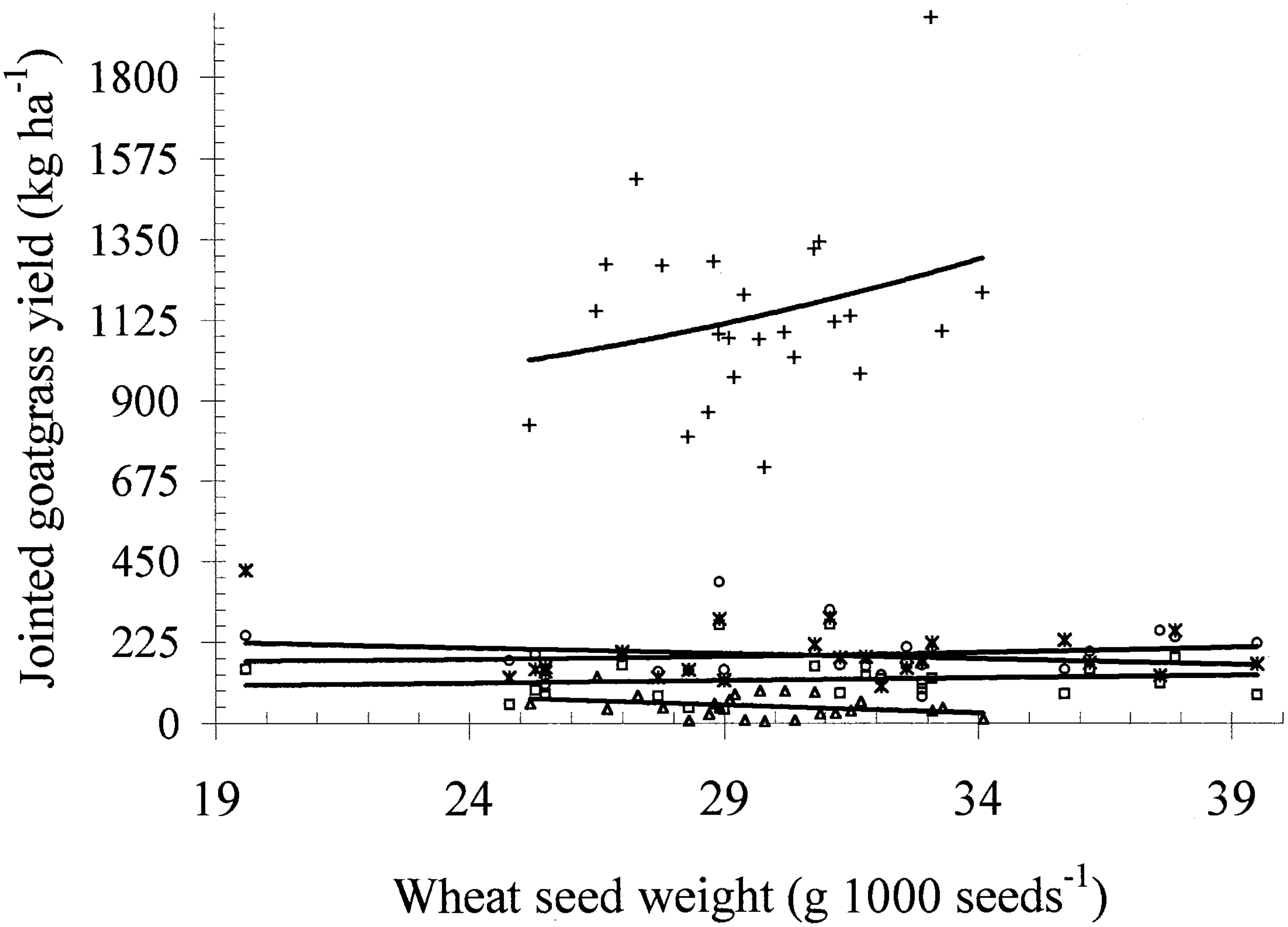
APPENDIX F. Effect of seed weight of 24 wheat cultivars on wheat stand (plants m^{-2}) at Chickasha (△): $y = 180.19 - 0.003x^3$, $R^2 = 0.09$; Lahoma (*): $y = 149.23 - 0.001x^3$, $R^2 = 0.22$; Orlando 1 (○): $y = 142.36 - 0.001x^3$, $R^2 = 0.23$; Orlando 2 (+): $y = 70.64 + 0.68x$, $R^2 = 0.03$; and Perkins (□): $y = 198.28 - 0.001x^3$, $R^2 = 0.15$.


Wheat emergence (plants m-2)
230
210
190
170
150
130
110
90
70
50
30
18
26
34
42
wheat seed weight (g 1000 seeds-1)

APPENDIX G. Effect of seed weight of 24 wheat cultivars on emergence (%) at Chickasha (△): $y = 65.38 - 0.001x^3$, $R^2 = 0.03$; Lahoma (*): $y = 42.75 + 0.31x$, $R^2 = 0.01$; Orlando 1 (○): $y = 29.22 + 0.81x$, $R^2 = 0.17$; Orlando 2 (+): $y = -8.57 + 1.17x$, $R^2 = 0.44$; and Perkins (□): $y = 41.65 + 1.09x$, $R^2 = 0.10$.


Wheat emergence (%)
100
90
80
70
60
50
40
30
20
18
23
28
33
38
Wheat seed weight (g 1000 seeds⁻¹)

APPENDIX H. Effect of seed weight of 24 wheat cultivars on jointed goatgrass (*Aegilops cylindrica* Host.) spikelet production (kg ha^{-1}) at Chickasha (△): $y = 144.08 - 3.58x$, $R^2 = 0.06$; Lahoma (*): $y = 223.38 - 2.36x$, $R^2 = 0.03$; Orlando 1 (○): $y = 128.36 + 0.001x^3$, $R^2 = 0.02$; Orlando 2 (+): $y = 823.33 + 0.01x^3$, $R^2 = 0.03$; and Perkins (□): $y = 61.38 + 1.14x$, $R^2 = 0.01$.



Jointed goatgrass yield (kg ha^{-1})
0
225
450
675
900
1125
1350
1575
1800
19
24
29
34
39
Wheat seed weight (g 1000 seeds^{-1})

APPENDIX I. Pearson correlation coefficients of the stand, vegetative growth, and grain yield of 24 cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) with NDVI recorded at 5, 10, 15, 4, and 14 intervals at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins, respectively.

Wheat attribute	Site[a]	Date of NDVI recording														
		20±1	35±5	47±1	55±1	69±3	76+1	85±1	90±4	103±3	109±5	120+1	129±3	135±3	144±1	156±4
		DAP[a]														
Stand	Ck	---	---	---	---	0.11[b]	---	---	---	---	---	-0.01	0.21‡	---	0.25‡	0.01
(plants m^{-2})	La	0.80‡	0.75‡	0.74‡	0.77‡	0.76‡	0.77‡	0.70‡	---	0.05	0.18†	---	---	0.71‡	---	0.66‡
	Or 1	0.46‡	0.61‡	0.39‡	0.58‡	0.55‡	0.60‡	0.51‡	0.58‡	0.57‡	0.49‡	0.04	0.48‡	0.39‡	0.20†	0.20†
	Or 2	---	---	---	---	---	-0.32‡	---	-0.34‡	---	-0.20‡	---	---	---	---	-0.11
	Pk	0.60‡	0.67‡	0.62‡	0.58‡	0.56‡	0.58‡	0.33‡	-0.18†	0.31‡	0.32‡	0.27‡	0.25‡	0.26‡	0.17†	---
Forage	Ck	---	---	---	---	0.13	---	---	---	---	---	-0.22†	0.22†	---	0.26†	0.07
(kg ha^{-1})	La	0.61‡	0.59‡	0.64‡	0.66‡	0.63‡	0.66‡	0.63‡	---	0.16	0.20†	---	---	0.59‡	---	0.86‡
	Or 1	0.27‡	0.41‡	0.22‡	0.38‡	0.37‡	0.39‡	0.29‡	0.37‡	0.37‡	0.31‡	0	0.27‡	0.34‡	0.26‡	0.23†
	Pk	0.53‡	0.62‡	0.63‡	0.60‡	0.69‡	0.60‡	0.54‡	-0.10	0.72‡	0.68‡	0.61‡	0.64‡	0.67‡	0.43‡	---
Height	La	0.61‡	0.59‡	0.70‡	0.72‡	0.73‡	0.75‡	0.76‡	---	0.09	0.28‡	---	---	0.88‡	---	0.86‡
Zad[a]. 32	Or 1	0.01	0.11	0.19†	0.26‡	0.29‡	0.26‡	0.28‡	0.36‡	0.36‡	0.39‡	0.05	0.49‡	0.45‡	0.53‡	0.47‡

(cm)	Pk	0.14	0.22‡	0.29‡	0.31‡	0.38‡	0.31‡	0.31‡	0.47‡	0.01	0.57‡	0.60‡	0.65‡	0.67‡	0.63‡	---
Zad. 37	Ck	---	---	---	---	0.16	---	---	---	---	---	0.05	0.11	---	0.34‡	0.19†
(cm)	La	0.58‡	0.57‡	0.68‡	0.67‡	0.68‡	0.69‡	0.67‡	---	0.04	0.25‡	---	---	0.81‡	---	0.82‡
	Or 1	-0.08	-0.02	-0.02	0.01	0.05	0.02	0.01	0.14	0.14	0.12	0.02	0.15	0.01	0.19†	0.18
	Pk	0	0.12	0.12	0.18†	0.19†	0.18†	0.20‡	-0.02	0.23‡	0.36‡	0.22‡	0.30‡	0.31‡	0.35‡	---
Zad. 91	Ck	---	---	---	---	0.14	---	---	---	---	---	0.27‡	-0.03	---	0.03	-0.03
(cm)	La	0.51‡	0.50‡	0.56‡	0.56‡	0.55‡	0.55‡	0.55‡	---	0.05	0.25‡	---	---	0.66‡	---	0.67‡
	Or 1	-0.19†	-0.17†	-0.01	-0.03	-0.15	-0.17†	-0.18†	-0.07	-0.07	-0.08	0.05	-0.05	-0.02	0.10	0.15
	Pk	0.16	0.20†	0.19	0.24‡	0.17†	0.24‡	0.12	0.19†	0.03	0.02	-0.04	-0.03	-0.04	0.01	---
Spikes	Ck	---	---	---	---	0.28‡	---	---	---	---	---	0.53‡	0.07	---	0.14	-0.07
Spks m^{-2}	La	0.46‡	0.51‡	0.60‡	0.62‡	0.81‡	0.81‡	0.80‡	---	0.07	0.25‡	---	---	0.71‡	---	0.71‡
	Or 1	-0.06	-0.07	0.15	0.02	0.01	0.01	0.10	0.07	0.07	0.12	-0.04	0.17	0.10	0.17†	0.17
	Pk	0.11	0.12	0.20	0.12	0.11	0.12	0.09	0.08	0.09	0.09	0.12	0.11	0.10	0.10	---
Yield	Ck	---	---	---	---	-0.09	---	---	---	---	---	0.08	-0.11	---	-0.29‡	-0.21‡
kg ha^{-1}	La	0.67‡	0.66‡	0.76‡	0.79‡	0.81‡	0.81‡	0.80‡	---	0.03	0.34‡	---	---	0.90‡	---	0.90‡
	Or 1	0.12	0.17†	0.17†	0.28‡	0.28‡	0.29‡	0.35‡	0.27‡	0.30‡	0.32‡	0.06	0.31‡	0.25‡	0.32‡	0.34‡
	Or 2	---	---	---	---	---	-0.04	---	0.28‡	---	0.16†	---	---	---	---	0.24‡

Pk	$0.18^{\dagger}$	0.14	0.15	0.13	$0.17^{\dagger}$	0.13	$0.16^{\dagger}$	0.05	$0.19^{\dagger}$	$0.19^{\dagger}$	$0.25^{\ddagger}$	$0.22^{\ddagger}$	$0.22^{\ddagger}$	$0.20^{\dagger}$	---

[a] Abbreviations: Days after planting, Ck, Chickasha; La, Lahoma; Or 1, Orlando year 1; Or 2, Orlando year 2; Pk, Perkins; Za, Zadocks.

[b] Pearson's correlation coefficient.

† Significant at the 0.05 level and ‡ significant at the 0.01 level

TABLE J. Pearson correlation coefficients between mean NDVI of 24 wheat cultivars at several dates growing under jointed goatgrass (*Aegilops cylindrica* Host.) free conditions with mean mature height, spike density, spikelet production, and spikelet density of jointed goatgrass grown with each of the 24 cultivars at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins.

AEGCY[a]		Date NDVI recorded (days after planting)														
attribute	Site[a]	20±1	35±5	47±1	55±1	69±3	76+1	85±1	90±4	103±3	109±5	120+1	129±3	135±3	144±1	156±4
Mature height	Ck	---	---	---	---	-0.23	---	---	---	---	---	-0.18	-0.08	---	-0.43	-0.39
(cm)	La	0.31	0.19	0.22	0.30	0.35	0.35	0.38	---	-0.20	-0.02	---	---	0.41	---	0.46
	Or 1	-0.15	-0.09	-0.21	-0.10	-0.07	-0.16	-0.22	-0.24	-0.21	-0.14	-0.28	-0.12	-0.10	-0.07	0.03
	Pk	-0.07	-0.06	-0.08	-0.17	-0.12	-0.17	-0.16	-0.09	-0.03	-0.04	0.08	-0.02	-0.05	-0.13	---
Spikes	Ck	---	---	---	---	-0.19	---	---	---	---	---	-0.25	-0.15	---	-0.47	-0.24
(no. m^{-2})	La	-0.53	-0.60	-0.58	-0.55	-0.48	-0.50	-0.49	---	0.04	-0.19	---	---	-0.50	---	-0.41
	Or 1	-0.41	-0.49	-0.34	-0.42	-0.33	-0.42	-0.33	-0.47	-0.56	-0.35	0.03	-0.30	-0.25	-0.13	0.18
	Pk	-0.73	-0.78	-0.76	-0.84	-0.83	-0.84	-0.84	0.12	-0.70	-0.65	-0.60	-0.65	-0.66	-0.67	---
Spikelet production	Ck	---	---	---	---	-0.23	---	---	---	---	---	-0.09	-0.11	---	-0.36	-0.16
(kg ha^{-1})	La	-0.75	-0.76	-0.75	-0.76	-0.75	-0.77	-0.66	---	0.39	-0.31	---	---	-0.63	---	-0.47
	Or 1	-0.50	-0.59	-0.47	-0.51	-0.44	-0.52	-0.41	-0.55	-0.62	-0.39	0.08	-0.34	-0.29	-0.21	0.09
	Or 2	---	---	---	---	---	-0.31	---	0.24	---	-0.30	---	---	---	---	0.01

	Pk	-0.69	-0.74	-0.69	-0.79	-0.80	-0.79	-0.76	0.13	-0.63	-0.59	-0.51	-0.52	-0.56	-0.56	---
Spikelets	Ck	---	---	---	---	-0.24	---	---	---	---	---	-0.04	-0.08	---	-0.32	-0.15
(no. m^{-2})	La	-0.76	-0.78	-0.76	-0.78	-0.76	-0.78	-0.67	---	0.40	-0.30	---	---	-0.65	---	-0.49
	Or 1	-0.58	-0.66	-0.54	-0.58	-0.50	-0.58	-0.47	-0.60	-0.67	-0.43	0.10	-0.37	-0.32	-0.23	0.06
	Or 2	---	---	---	---	---	-0.40	---	0.20	---	-0.41	---	---	---	---	0.03
	Pk	-0.69	-0.74	-0.69	-0.79	-0.80	-0.79	-0.75	0.14	-0.61	-0.57	-0.50	-0.50	-0.54	-0.53	---

[a] Abbreviations: AEGCY, jointed goatgrass (*Aegilops cylindrica*); Ck, Chickasha; La, lahoma; Or 1, Orlando year 1; Or 2, Orlando year 2; Pk, Perkins.

[b] Pearson's correlation coefficient

APPENDIX K. Pearson correlation coefficients of the mean wheat stand, vegetative growth, and grain yield of 24 cultivars grown without jointed goatgrass (*Aegilops cylindrica* Host.) with mean NDVI recorded at 5, 10, 15, 4, and 14 intervals at Chickasha, Lahoma, Orlando 1, Orlando 2, and Perkins, respectively.

Wheat attribute	Site[a]	Date of NDVI recording 20±1	35±5	47±1	55±1	69±3	76+1	85±1	90±4	103±3	109±5	120+1	129±3	135±3	144±1	156±4
		days after planting														
(plants m^{-2})	La	0.82	0.85	0.77	0.83	0.84	0.83	0.58	---	-0.16	0.17	---	---	0.56	---	0.51
	Or 1	0.53	0.71	0.57	0.67	0.64	0.70	0.64	0.71	0.72	0.60	-0.29	0.48	0.42	0.29	0.02
	Or 2	---	---	---	---	---	0.23	---	-0.12	---	0.05	---	---	---	---	-0.07
	Pk	0.78	0.88	0.82	0.84	0.84	0.84	0.72	-0.32	0.61	0.55	0.54	0.47	0.48	0.44	---
Forage	Ck	---	---	---	---	0.15	---	---	---	---	---	0.35	0.18	---	0.23	-0.17
(kg ha^{-1})	La	0.68	0.72	0.83	0.78	0.74	0.74	0.83	---	0.05	0.01	---	---	0.72	---	0.60
	Or 1	0.25	0.42	0.46	0.46	0.54	0.47	0.46	0.45	0.50	0.44	-0.46	0.32	0.44	0.42	0.30
	Pk	0.57	0.74	0.74	0.76	0.84	0.77	0.88	-0.23	0.95	0.89	0.86	0.87	0.86	0.72	---
Height	La	0.40	0.41	0.49	0.48	0.47	0.48	0.58	---	-0.45	0.38	---	---	0.72	---	0.63
Zad[a]. 32	Or 1	-0.05	0.00	0.09	0.07	0.12	0.06	0.11	0.17	0.21	0.38	-0.20	0.45	0.44	0.58	0.47
(cm)	Pk	0.11	0.17	0.25	0.29	0.36	0.29	0.49	-0.06	0.62	0.61	0.65	0.71	0.73	0.75	---

Zad. 37	Ck	---	---	---	---	0.21	---	---	---	---	---	0.10	-0.01	---	0.38	0.33
(cm)	La	0.27	0.29	0.40	0.34	0.33	0.34	0.28	---	-0.24	0.47	---	---	0.43	---	0.42
	Or 1	-0.12	-0.11	-0.17	-0.16	-0.16	-0.19	-0.22	-0.10	0.04	-0.02	-0.16	-0.02	-0.10	0.15	0.07
	Pk	0.01	0.16	0.18	0.27	0.32	0.27	0.43	-0.21	0.43	0.46	0.36	0.44	0.49	0.54	---
Zad. 91	Ck	---	---	---	---	0.17	---	---	---	---	---	-0.06	-0.18	---	0.00	0.12
(cm)	La	0.19	0.23	0.22	0.17	0.10	0.10	0.04	---	0.10	0.37	---	---	0.10	---	0.04
	Or 1	-0.14	-0.18	-0.24	-0.20	-0.21	-0.27	-0.30	-0.23	-0.22	-0.24	0.02	-0.22	-0.17	-0.04	-0.19
	Pk	0.30	0.32	0.28	0.39	0.33	0.39	0.26	0.18	0.10	0.05	-0.04	-0.04	-0.06	0.02	---
Spikes	Ck	---	---	---	---	0.39	---	---	---	---	---	0.24	0.20	---	0.03	0.08
Spks m^{-2}	La	-0.01	0.04	-0.10	0.01	0.00	0.00	-0.10	---	0.13	-0.28	---	---	-0.10	---	-0.16
	Or 1	0.03	-0.11	0.09	-0.08	-0.09	-0.08	-0.01	-0.02	-0.07	0.02	0.12	0.06	0.08	0.07	0.17
	Pk	0.33	0.24	0.20	0.21	0.25	0.21	0.24	-0.19	0.29	0.30	0.34	0.35	0.41	0.39	---
Yield	Ck	---	---	---	---	-0.36	---	---	---	---	---	-0.26	-0.15	---	-0.38	-0.41
kg ha^{-1}	La	0.47	0.52	0.53	0.58	0.63	0.63	0.59	---	-0.43	0.13	---	---	0.62	---	0.61
	Or 1	0.31	0.42	0.45	0.47	0.57	0.51	0.51	0.47	0.42	0.49	-0.29	0.43	0.46	0.45	0.38
	Or 2	---	---	---	---	---	-0.13	---	0.01	---	-0.14	---	---	---	---	-0.18
	Pk	0.28	0.19	0.13	0.17	0.22	0.17	0.23	-0.01	0.26	0.29	0.34	0.28	0.27	0.27	---

[a] Abbreviations: Ck, Chickasha; La, Lahoma; Or 1, Orlando year 1; Or 2, Orlando year 2; Pk, Perkins; Za, Zadocks.

VITA 2

Amanda Elizabeth Stone

Candidate for the Degree of

Doctor of Philosophy

Thesis: OPTICAL AND HUMAN ASSESSMENT OF WINTER WHEAT CULTIVARS FOR COMPETITIVENESS AGAINST JOINTED GOATGRASS, AND CHARACTERIZING OKLAHOMA JOINTED GOATGRASS-WINTER WHEAT HYBRIDS

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