



Winter Wheat Blends (Mixtures) Produce a Yield Advantage in North Carolina

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ABSTRACT

Seed mixtures, or blends, of small grain cultivars are unknown in eastern U.S. wheat production, where numerous diseases and abiotic stresses often reduce yield and quality. In 2004–2005 and 2005–2006, a field experiment was conducted at Kinston, Plymouth, and Salisbury, NC, to compare performance of eight soft red winter wheat (*Triticum aestivum* L.) cultivars having a range of maturities with that of 13 blends, each consisting of equal proportions of two or three of the cultivars. The blends were composed to have complementary disease resistance traits. Disease pressure was at most moderate in any environment. Blends significantly outyielded the means of their respective components (midcomponents) in Plymouth in 2005 ($P = 0.042$) and across all environments ($P = 0.039$), with a mean overall blend advantage of 0.13 Mg ha^{-1} . Averaged across environments, two blends significantly outyielded their midcomponents ($P \leq 0.011$). Yield stability of blends exceeded that of pure cultivars by the stability variance model and principal component analysis. In general, blends did not differ significantly from midcomponents for test weight ($P = 0.37$), protein content ($P = 0.10$), hardness ($P = 0.68$), or falling number (sprouting tolerance, $P = 0.89$), but seed diameter nonuniformity of blends exceeded that of midcomponents ($P = 0.0002$). Wheat blends may offer a small yield advantage to North Carolina growers even in the absence of severe disease.

SOFT RED WINTER WHEAT is the predominant market class of wheat in the eastern United States, and is planted on approximately 3 million hectares there annually [1997–2006 average, (NASS, 2007)]. In this region of the United States, wheat is grown in rotation with maize (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.], and is often a relatively low-profit crop for which unnecessary inputs must be minimized (Weisz, 2004). Over the entire region, yields average approximately 3.4 Mg ha^{-1} , with a statewide mean range of 2 to 4.6 Mg ha^{-1} (NASS, 2007). Yields are affected by a range of diseases, and by environmental heterogeneity, including a wide variety of soil types, nutrient stresses, freeze damage, and water over- or undersupply.

Cultivar blends have been used extensively in small grain production in several European countries (Wolfe, 2001). Currently, 6 to 15% of the wheat production area in the states of Washington, Oregon, and Kansas is planted to blends every year (NASS, 2007). However, small grain blends are unknown in eastern U.S. wheat cultivation.

Blends have been thoroughly reviewed (Mundt, 2002; Smithson and Lenne, 1996; Wolfe, 1985). Among their potential advantages are yield stabilization across diverse environments, the reduction of within-season disease build-

up, and increased durability of deployed disease resistances through delay in the build-up of new races of major pathogens and reduced selection for improved fitness within those races (Wolfe, 1985).

The performance of an individual blend is often evaluated by comparing its performance in a given parameter, such as yield, quality, or disease severity, to the mean of that parameter for the pure cultivars that constitute that blend. The mean of the components is also referred to as the midcomponent (Essah and Stoskopf, 2001). Smithson and Lenne (1996) summarized the yield results from more than 100 studies of intraspecific field crop blends, and concluded that on average blend yields exceeded their midcomponents by a small but significant amount, and the advantage was greater for wheat (5.4%) than other field crops. More recent peer-reviewed (Østergård et al., 2005) and non-peer-reviewed (Kessler, 1997; Swallow and Abel, 2002) reports have indicated yield advantages to small grain blends.

Yield stability is one of the main benefits reported for blends. Smithson and Lenne (1996) analyzed 35 data sets of yields of blends and their components for genotype \times environment interaction, using analysis of variance and regression, and concluded that blend yields almost always varied less among environments than did the yields of blend components. Østergård et al. (2005) grew six three-component spring barley (*Hordeum vulgare* L.) blends and their components in 17 environments, and found that blends were on average more stable than pure cultivars both in actual yield and in yield ranking.

The effect of different numbers of blend components has been studied, and the evidence on whether increased com-

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Table 1. Plant introduction/plant variety protection (PI/PVP) numbers, maturities, and heights of eight soft red winter wheat cultivars used in a 2005–2006 blend experiment in North Carolina.

Cultivar	PI/PVP no.	Maturity (day of year) [†]	3-yr mean plant ht. [‡]
AGS 2000	PI 612956	102	89
McCormick	PI 632691	107	84
NC Neuse	PI 633037	108	84
Pioneer 26R12	200200234	108	86
Roane	PI 612958	110	81
Vigoro Tribute	PI 632689	103	79
USG 3209	200100127	107	79
USG 3592	200400110	106	91

[†] 2006 heading dates, North Carolina Official Variety Trial (Bowman, 2006).

[‡] Mean of 2004–2006 data (Bowman, 2006).

ponent number correlates with yield improvement is mixed (Smithson and Lenne, 1996). In at least three studies of small grains, blend yield advantages were greater with more than two components than with just two (Newton et al., 1997; Nitzsche and Hesselbach, 1983; Stuke and Fehrmann, 1987). Nitzsche and Hesselbach (1983) studied blends of spring barley and reported that yield increased as the number of components in the blends increased from two to six. Smithson and Lenne (1996) reported that yield stability of field crop blends improved with increasing numbers of components in about half the datasets they examined.

There may be a relationship between component diversity and blend advantage, although the evidence is not uniform (Smithson and Lenne, 1996). Some studies of soybean blends with components divergent in yield, plant height, and/or maturity have shown a positive relationship between mixture advantage and component diversity (Mumaw and Weber, 1957; Schweitzer et al., 1986; Smithson and Lenne, 1996). Another study showed no relationship between mixture advantage and maturity differences in soybean cultivars (Gizlice et al., 1989). Essah and Stoskopf (2001) blended barley cultivars that varied in stature and maturity, and found a yield advantage to blending early with late cultivars, as long as the maturity difference was not too great. They hypothesized that the early:late combination allowed the plants to maximally exploit their environment.

Blends are thought to help reduce disease by diluting the inoculum efficiency of airborne foliar pathogens, through a barrier effect created by resistant plants, and by induced resistance when nonpathogenic spores trigger systemic defenses that help protect plants against pathogenic strains (Wolfe, 1985). Other mechanisms that may help account for yield advantages in blends include complementary patterns of canopy or root architecture, leading to more efficient utilization of light or water; complementary nutrient exploitation; compensation for neighboring plants killed or weakened by environmental stress; and mechanical factors, such as a less lodging-prone component propping up a more lodging-prone one (Essah and Stoskopf, 2001; Smithson and Lenne, 1996; Trenbath, 1974).

Individual blends may have positive, neutral, or negative effects on yield, and thus blends must be tested under varying conditions before recommendations can be made (Mundt

et al., 1995a, 1995b). It would be desirable to plant blends in small unit areas, to screen the largest possible number of component combinations each year. However, blend benefits are probably greater at larger spatial scales, as host-diversity effects on disease may increase over larger areas (Garrett and Mundt, 1999; Mille et al., 2006; Wolfe, 1985). This is due in part to the fact that, at least for some wind-dispersed foliar diseases, the velocity of disease expansion increases with distance from inoculum source (Cowger et al., 2005; Ferrandino, 1993). Thus, the difference in epidemic velocity between pure and mixed stands will become greater over larger distances, giving an increased host-diversity advantage at larger spatial scales. An increasing blend advantage at larger spatial scales has been observed experimentally (Mille et al., 2006; Wolfe, 1985; Zhu et al., 2000).

We sought to determine whether cultivar blends could help stabilize yields across diverse production environments in the southeastern United States, and whether grain from blends would maintain softness, diameter uniformity, sprouting tolerance, and protein content within acceptable tolerances for millers purchasing grain for flour. We evaluated blends in large and small plots to test the effect of plot size on blend effect.

MATERIALS AND METHODS

Cultivar Selection and Agronomics

The genotypes selected for blending were released cultivars with good adaptation to North Carolina and of varying maturity (Table 1). Cultivars were chosen for blending based on their complementarity for disease resistance characteristics, and were selected without any prior knowledge of their performance in blends. Hereafter, blends and pure cultivars will be referred to generically as “entries.”

Field plots of soft red winter wheat were established in the 2004–2005 and 2005–2006 growing seasons (hereafter termed “2005” and “2006”) at three North Carolina locations, which will be referred to as Salisbury, Kinston, and Plymouth. In 2005, the Salisbury experiment at the Piedmont Research Station (35°42′0″ N, 80°37′12″ W, 214 m elevation) was planted in a Chewacla soil (fine-loamy, mixed, active, thermic Fluvaquentic Dystrudepts). In 2006, the experiment at that same location was planted in a Hiwassee clay loam (fine, kaolinitic, thermic Rhodic Kanhapludults). In both years, the Kinston experiment at the Cunningham Research and Extension Center location (35°17′60″ N, 77°28′12″ W, 29 m elevation) was planted in a Rains sandy loam (fine-loamy, siliceous, semiactive, thermic Typic Paleaquults). In both years, the Plymouth experiment at the Tidewater Research Station (35°52′12″ N, 76°39′0″ W, 6 m elevation) was planted in a Portsmouth fine sandy loam (fine-loamy over sandy or sandy-skeletal, mixed, semiactive, thermic Typic Umbraquults). Combinations of location and year will be referred to as environments. Respectively, the three locations of Salisbury, Kinston, and Plymouth are in the North Carolina Piedmont region, where heavy clay soils predominate; the Coastal Plain, with a sandy loam; and the Tidewater zone, where heavy organic soils prevail. The most common and damaging diseases in these locations are barley yellow dwarf virus in the Piedmont; powdery mildew (caused by *Blumeria graminis* f. sp. *tritici*) and

leaf rust (caused by *Puccinia triticina*) in the Coastal Plain; and leaf rust in the Tidewater.

At Kinston and Plymouth, two plot sizes were used to investigate whether plot size influenced blend performance. Large plots were planted in the same field as small plots. After end-trimming, large plots measured 6.1 m in length and 3.1 m in width. Each small plot consisted of two adjacent rows and measured 1.83 m in length and 0.31 m in width. Seed was drilled in each plot to a depth of 3 cm. To minimize interplot interference, buffer plots of barley were interspersed in a checkerboard pattern. The barley plots were of the same size as the wheat plots in both the large-plot and small-plot experiments. Borders of barley were planted around each experiment.

Planting dates for all environments were within recommended time windows (Weisz, 2004). In the first year, planting occurred in Salisbury on 20 October, in Kinston on 23 October, and in Plymouth on 9 November. In the second year, large plots were planted in Salisbury on 19 October, in Kinston on 21 October, and in Plymouth on 3 November; small plots were planted in Kinston on 2 November and in Plymouth on 7 November.

Each of 13 blends (Table 2) was prepared with equal numbers of seeds of each component cultivar. Seeding rates were 337 seeds per m² in the large plots, and 340 seeds per m² in the small plots. These rates were in line with the statewide recommendation of 322 to 377 seeds per m² (Weisz, 2004).

All trials were planted in conventionally tilled fields following corn or soybean. Recommended practices appropriate to each site were followed with respect to soil preparation, fertilization, and applications of herbicides and insecticides (Weisz, 2004).

Tiller Counts

Where blend components could be visually distinguished, tillers were counted before harvest to determine how the blend proportions at harvest compared to the planted ratios of 1:1 or 1:1:1. In 2005, tillers could be counted in all blend plots using presence or absence of awns, spike color, and presence or absence of powdery mildew lesions as identifying characteristics. In 2006, tiller counts could only be reliably performed on four blends, as disease incidence was insufficient to distinguish cultivars in the other blends. Counts were conducted as follows: in each of two or three replicates per environment, a group of 25 to 30 tillers was chosen blindly in

Table 2. Yields from large field plots of pure cultivars and two- and three-component blends of soft red winter wheat in North Carolina. Data are means of three replicates in six environments.

No.	Entry	Site						Yield†	Rank
		Salisbury		Kinston		Plymouth			
		2005	2006	2005	2006	2005	2006		
		Mg ha ⁻¹							
1	AGS 2000	5.33	5.41	5.12	4.88	5.08	3.69	4.92	7
2	McCormick	5.18	4.69	4.16	4.09	5.30	2.63	4.34	20
3	NC Neuse	4.79	4.45	4.54	4.84	4.77	4.03	4.57	15
4	P26R12	4.97	5.46	4.76	5.67	5.82	4.27	5.16	2
5	Roane	5.13	4.60	4.18	4.02	4.68	3.16	4.30	21
6	Tribute	5.02	4.90	3.93	4.68	4.81	3.03	4.40	19
7	USG 3209	5.96	5.96	5.83	4.42	5.38	2.83	5.06	3
8	USG 3592	5.10	5.43	4.60	4.60	5.51	3.42	4.78	10
9	AGS 2000/P26R12	5.28	5.53	5.04	5.77	5.71	3.72	5.17	1
10	AGS 2000/USG 3209	5.65	5.87	5.01	4.39	5.19	3.32	4.91	8
11	McCormick/Roane	4.99	5.30*	4.41	4.17	5.22	2.84	4.49	18
12	McCormick/USG 3592	5.13	4.85	4.84	4.57	5.19	3.29	4.65	13.5
13	NC Neuse/Roane	5.37	5.33**	4.27	4.41	5.16	3.34	4.65	13.5
14	NC Neuse/USG 3592	5.12	5.12	5.15	5.26	5.76	3.83	5.04*	4
15	P26R12/USG 3209	5.70	4.86‡	5.01	4.91	5.69	3.63	4.97	6
16	Roane/Tribute	5.12	5.16	4.46	4.43	4.68	3.42	4.54	17
17	Tribute/USG 3592	4.88	5.43	4.74	4.58	5.13	3.48	4.71	11
18	AGS 2000/P26R12/USG 3209	5.42	4.89§	5.40	5.17	5.80	3.28	4.99	5
19	McCormick/Neuse/Roane	4.68	4.98	4.90*	5.04**	5.44	3.83*	4.81**	9
20	NC Neuse/Roane/Tribute	4.91	5.04	4.12	4.30	5.37	3.63*	4.56	16
21	NC Neuse/Tribute/USG 3592	5.10	5.22	4.75	4.54	5.16	3.42	4.70	12
Means									
Midcomponents		5.15	5.04	4.58	4.62	5.11	3.40	4.65	
Blends		5.18	5.19	4.79	4.75	5.38*	3.49	4.80*	

* Blend significantly outyielded mean of its component pure cultivars at the 0.05 probability level.

** Blend significantly outyielded mean of its component pure cultivars at the 0.01 probability level.

† LSD among entries in this column only = 0.29 Mg ha⁻¹.

‡ Blend yielded significantly less than the mean of its component pure cultivars at the 0.01 probability level.

§ Blend yielded significantly less than the mean of its component pure cultivars at the 0.05 probability level.

each of the four plot quadrants. Tiller counts were only taken in the small plots in 2005.

Harvest and Grain Analysis

All large plots were harvested by combine each year, and moisture content and test weight were determined on a grain analysis computer (GAC 2100, Dickey-John Corp., Auburn, IL). Small plots were hand-harvested and threshed using a stationary thresher (Wintersteiger LD350). Yields were determined by adjusting the grain weight of samples by their moisture content, using the mean moisture content for that environment (12.5–14%).

Four quality tests were performed on each sample. Kernel size uniformity (diameter and its standard deviation) and hardness were determined on a Perten SKCS 4100 (Perten Instruments, Springfield, IL). Samples were milled using a Perten Laboratory Mill 3100. The protein content of the flour was determined on a Percon Inframatic 8620 near-infrared spectrometer (Perten Instruments NA, Inc., Reno, NV). The flour was also analyzed for sprouting damage on a Perten FN 1500 falling number machine.

Data Analysis

Yield, test weight, and quality data were analyzed separately using PROC MIXED (SAS Institute, Cary, NC).

Entry was considered a fixed effect, and year, site nested within year, replicate nested within site \times year, and site \times year \times entry were treated as random effects. Contrasts were used to compare the means of blends to those of their component pure cultivars. To compare the mean of blend performance with the mean of pure-cultivar performance, pure cultivars were weighted according to how often they appeared in the blends. This was done in the contrasts by summing the coefficients of the individual blends and their component pure cultivars.

In addition, the proportion of total variation associated with each effect was determined by defining all sources of variation in the PROC MIXED model above as random effects, and then computing their respective estimated variances as percentages of the total model variance.

SAS PROC FREQ was used to analyze tiller counts. The “testp” option was used to test whether tiller proportions varied significantly from equiproportional.

Test weight discount schedules were collected from three mills in North Carolina and one in Virginia, all wishing to remain anonymous. The discounts were averaged to create a sample schedule to which experimental test weights could be compared.

Yield stability of an entry was estimated by its ability to maintain optimal yield across environments. Two methods were used to evaluate stability of blends compared to pure cultivars. The first method was biplot analysis, conducted with the GGEBiplot program (Yan, 2001), version 3.7.31, on yield means of all entries at all environments. A biplot is a scatter plot that graphically displays a rank-two matrix that approximates a two-way table, using the first two principal components, PC1 and PC2. In this case, the rows of the table were entries and the columns were sites. Biplots were generated based on an environment-centered model (Yan, 2005),

$$p_{ij} = y_{ij} - \mu - \beta_j = \alpha_i + \phi_{ij}$$

where p_{ij} is an element of a rank-two matrix, y_{ij} is the value of cultivar i in environment j , μ is the grand mean, β_j is the environment main effect, α_i is the cultivar main effect, and ϕ_{ij} is the cultivar-by-environment interaction. The form of singular value decomposition (SVD) used was environment-metric or column-metric preserving (Yan, 2005). The yield stability of an entry corresponds to its angular separation from the average environment axis, which passes through the

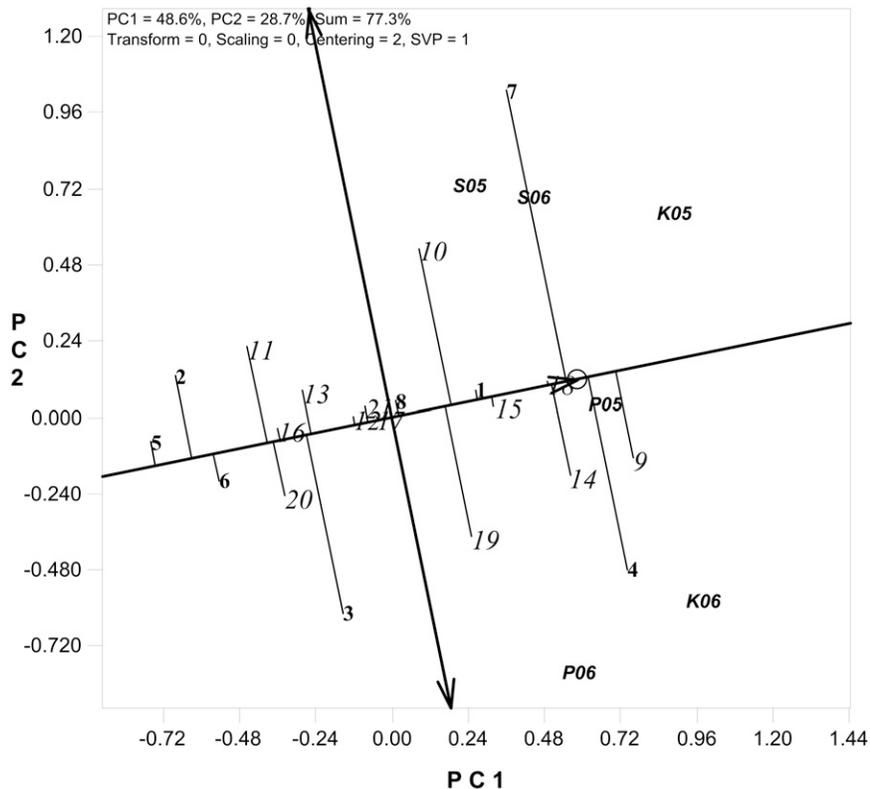


Fig. 1. Biplot illustrating principal component analysis of yield data from 6.1 by 3.1 m field plots of eight pure cultivars and 13 two- and three-component blends (21 entries total) of soft red winter wheat planted in six environments in North Carolina. Sites were Kinston (K) in the Coastal Plain, Plymouth (P) in the Tidewater region, and Salisbury (S) in the Piedmont, and years were 2005 (05) and 2006 (06). There were three replicates of each entry at each environment. Entry numbers are from Table 1. Numbers 1 through 8 are pure cultivars (bold type), while the blends (italic type), 9 through 17 had two components, and 18 through 21 had three components. Higher-yielding entries are to the right, lower-yielding entries to the left. The open circle at tip of arrow on the nearly horizontal average environment axis (AEA) indicates “ideal entry.” The most stable entries are those closest to the AEA.

biplot origin and the average or “ideal” environment (Yan and Kang, 2003).

The second method for evaluating yield stability began with a comparison of methods following Piepho (1999), using his SAS code for PROC MIXED. Shukla’s (1972) stability variance model for randomized complete block designs was chosen due to its superior fit by Akaike’s Information Criterion.

RESULTS

Disease and Growing Conditions

In 2005, conditions for wheat growth at all experimental locations were excellent, as a cool spring led to high mean yields and test weights, and diseases generally played minor roles. In 2006, parts of the state wheat crop (including the present experiment) were affected by Hessian fly (*Mayetiola destructor*) and periods of waterlogging and drought. Average North Carolina yields were above the 10-yr mean yield in both years (NASS, 2007).

Yield

Yields and entry ranks from the large plots are reported in Table 2. Blends significantly outyielded pure cultivars in Plymouth in 2005 ($P = 0.042$) and across all environments ($P = 0.039$), with a mean overall blend advantage of 0.13 Mg ha^{-1} . Averaged across environments, two blends significantly outyielded their midcomponents: NC Neuse/USG3592 ($P = 0.032$) and McCormick/NC Neuse/Roane ($P = 0.011$). In individual environments, blends outyielded midcomponents in six cases, and midcomponents outyielded blends in two cases, both in Salisbury in 2006.

In Fig. 1, the entries in the large plots are indicated with the numbers in Table 1 for readability. Entries toward the right were higher yielding, while those toward the left were lower yielding. Three of the five highest-yielding entries were blends: AGS2000/P26R12 (Entry 9), NC Neuse/USG 3592 (Entry 14), and AGS 2000/P26R12/USG 3209 (Entry 18).

All entries to the right of the nearly vertical axis tipped by a downward-pointing arrow yielded above average for the experiment. Along with P26R12 (Entry 4), the above-average yielding blends tended to perform better in Kinston and Plymouth than in Salisbury, as indicated by their greater proximity to three of the four Kinston and Plymouth environments in the biplot. Figure 1 shows that these three Kinston and Plymouth environments were more similar (closer together) to each other in their ranking of entries than was any of them to Salisbury. Along with Table 2, these data indicate that tested blends performed better at the Coastal Plain and Tidewater sites, which are both in eastern North Carolina, than at the Piedmont site in the west-central part of the state. Of total variation, 4% was due to entry, 59% to environment, and 10% to genotype-by-environment interaction.

In small plots, there were no significant differences between yields of blends and their midcomponents (data not shown). The estimate of the mean difference between blend and midcomponent yields was 0.053 Mg ha^{-1} , $P =$

Table 3. Stability of yields from field plots of pure cultivars and two- and three-component blends of soft red winter wheat in North Carolina, with three replicates of each treatment in each of six environments.

No.	Entry	GGE Biplot instability (abs value)†	Shukla’s stability variance model‡	
			Variance estimate	Standard error
1	AGS 2000	0.104	0	–
2	McCormick	0.399	0.0713	0.0813
3	NC Neuse	1.128	0.1782	0.1492
4	P26R12	1.073	0.1683	0.1431
5	Roane	0.027	0.0001	0.0364
6	Tribute	0.252	0.0210	0.0491
7	USG 3209	1.866	0.4226	0.3034
8	USG 3592	0.094	0	–
9	AGS 2000/P26R12	0.410	0.0766	0.0849
10	AGS 2000/USG 3209	0.984	0.0926	0.0952
11	McCormick/Roane	0.529	0.0297	0.0551
12	McCormick/USG 3592	0.035	0	–
13	NC Neuse/Roane	0.227	0.0033	0.0389
14	NC Neuse/USG 3592	0.474	0.0419	0.0634
15	P26R12/USG 3209	0.007	0.0422	0.0627
16	Roane/Tribute	0.021	0	–
17	Tribute/USG 3592	0.018	0	–
18	AGS 2000/P26R12/USG 3209	0.105	0.1272	0.1166
19	McCormick/Neuse/Roane	0.762	0.0799	0.0875
20	NC Neuse/Roane/Tribute	0.390	0.0314	0.0556
21	NC Neuse/Tribute/USG 3592	0.088	0	–
	Mean pure cultivar	0.618	0.1077	0.0953
	Mean blend	0.312	0.0404	0.0508

† Projection away from Average Environment Axis in Fig. 1.

‡ Shukla’s (1972) stability variance model for randomized complete block designs; yield variance of each entry estimated by restricted maximum likelihood (REML).

0.84. Considering individual environments, blends and midcomponents were never significantly different either for an environment overall or for an individual blend within an environment, with the sole exception of P26R12/USG3209, which yielded less than its midcomponent in Plymouth in 2006 ($P = 0.033$).

Yield Stability

In Fig. 1, the average environment axis (AEA) is nearly horizontal and bears an arrow pointing to a small open circle, which signifies the “ideal” (most broadly successful) entry in the experiment. A greater projection of an entry from the AEA is negatively associated with the yield stability of that entry across all test sites (Yan, 2005). The best performance of the entry was in the site to which it appears closest. According to the instability values provided by GGEbiplot for each entry (Table 3), mean blend instability was lower than mean pure cultivar instability. Of the five highest-yielding entries, the three blends were all more yield-stable (closer to the AEA) than the two pure cultivars. The blends AGS 2000/P26R12 (Entry 9) and AGS 2000/P26R12/USG 3209 (Entry 18) were closest to the “ideal entry.”

Shukla’s stability variance model also indicated that blends were more yield-stable than pure cultivars in this experiment (Table 3). The means of both the estimates of entry variance and the standard errors associated with those means were lower for blends than for pure culti-

vars. The stability variance model agreed with GGEbiplot on the three least stable entries (NC Neuse [Entry 3], P26R12 [Entry 4], and USG 3209 [Entry 7]). Otherwise, there was general correspondence in the results of the two models, with some differences in rankings (in particular, for entries 11, 15, and 18).

Test Weights

None of the four mills surveyed discounted the price of wheat with a test weight ≥ 746 kg m^{-3} . The average published test weight discount of the four mills was \$0.71 Mg^{-1} for test weights of 740 to 745 kg m^{-3} ; \$1.10 Mg^{-1} for test weights of 734 to 739 kg m^{-3} ; \$1.77 Mg^{-1} for test weights of 727 to 733 kg m^{-3} ; and \$2.48 Mg^{-1} for test weights of 721 to 726 kg m^{-3} . Only one of the mills accepted wheat with a test weight below 721 kg m^{-3} .

Mean test weights varied among the environments (Table 4). Test weights were particularly low in 2006 in both Salisbury and Kinston, likely due to spring drought and fall Hessian fly infestation, respectively.

Averaged across environments, test weights of blends were not significantly different from those of pure cultivars ($P = 0.37$, Table 4). However, one blend had a test weight significantly lower than the mean of its component pure cultivars, when averaged across environments ($P = 0.02$). The mean test weight for this blend, McCormick/Roane, was 755 kg m^{-3} across environments, a value above the threshold at which dockage occurs. This blend had a test weight significantly lower than that of its midcomponent in two of the six individual environments (Kinston 2006, $P = 0.01$, and Salisbury 2006, $P = 0.02$), and significantly higher than that of its midcomponent in one environment (Plymouth 2006, $P = 0.02$). In individual environments, three other blends had test weights significantly lower than those of their respective midcomponents, although in two cases the test weight of the blend was still above the dockage threshold. In the third case, P26R12/USG 3209 in Plymouth 2006, the test weight of the blend was 729 kg m^{-3} , which would have resulted in mean dockage of \$1.77 Mg^{-1} , while the mean test weights of both component pure cultivars were above the dockage threshold.

Quality

The desired hardness range for soft wheat, using the Single-Kernel Characterization System (SKCS) Hardness Index, is <40.0 for pastry flour and 10.0 to 40.0 for cracker and export flour (Souza, 2007). Hardness of the pure cultivars in our experiment is given in Table 5. Across environments, blends and midcomponents did not differ significantly in hardness either as a whole (blends vs. midcomponents, $P = 0.68$) or in the comparisons of individual blends to their respective midcomponents (data not shown).

Table 4. Test weights from field plots of selected pure cultivars and two- and three-component blends of soft red winter wheat in North Carolina, with three replicates of each treatment in each environment.

Entry	Site						Mean
	Salisbury		Kinston		Plymouth		
	2005	2006	2005	2006	2005	2006	
	kg m^{-3}						
AGS 2000	761	733	777	749	776	764	760
McCormick	776	749	803	725	803	753	768
NC Neuse	767	700	792	739	800	766	761
P26R12	750	709	790	738	800	759	758
Roane	781	731	803	750	813	745	770
Tribute	784	757	800	744	815	771	778
USG 3209	761	723	775	674	771	752	743
USG 3592	762	703	789	728	798	759	757
AGS 2000/P26R12	760	728	779	731	792	757	758
AGS 2000/USG 3209	762	729	774	725	777	756	754
McCormick/Roane	773	703*	798	677*	807	770†	755*
McCormick/USG 3592	767	731	798	688	802	763	758
NC Neuse/Roane	772	701	797	702	808	768	758
NC Neuse/USG 3592	769	722	792	752	801	760	766
P26R12/USG 3209	757	709	778	707	785	729†	744
Roane/Tribute	780	739	805	755	812	773	777
Tribute/USG 3592	778	720	795	745	800**	768	768
AGS 2000/P26R12/USG 3209	762	711	775*	719	778	759	751
McCormick/Neuse/Roane	777	722	803	719	807	769	766
NC Neuse/Roane/Tribute	775	717	802	721	809	770	766
NC Neuse/Tribute/USG 3592	772	716	796	731	805	768	765
Means							
Midcomponents	769	725	792	733	799	759	763
Blends	772	721	794	723	801	765	763

* Test weight of blend significantly lower than the mean of its component pure cultivars at the 0.01 probability level.

** Test weight of blend significantly lower than the mean of its component pure cultivars at the 0.05 probability level.

† Test weight of blend significantly higher than the mean of its component pure cultivars at the 0.05 probability level.

Table 5. Quality data from field plots of selected pure cultivars and two- and three-component blends of soft red winter wheat in North Carolina. Data are means across six environments, with three replicates of each treatment in each environment.

Cultivar	Hardness†	Kernel diameter	Falling number‡	Protein§
		mm	s	
AGS 2000	11.2	2.72	427	113
McCormick	30.7	2.30	414	107
NC Neuse	25.3	2.72	404	115
Pioneer 26R12	20.8	2.70	380	104
Roane	30.2	2.43	404	106
Vigoro Tribute	30.7	2.56	410	106
USG 3209	26.3	2.65	428	105
USG 3592	17.1	2.57	360	101

† The desired range for soft wheat milled for crackers and cookies is <40.0 for pastry flour and 10.0 to 40.0 for cracker and export flour (Souza, 2007).

‡ The desired range is >350 s.

§ The desired range for soft wheat is 80 to 100 g kg^{-1} for pastry flour, and 90 to 140 g kg^{-1} for cracker and export flour.

For environments individually, there was no significant difference between mean blend and midcomponent hardness. Within environments, blends differed significantly from their respective midcomponents in hardness in nine instances. In one case, blend and midcomponent had hardness of 30.3 and 27.8, respectively. In all other cases, either blends were softer than respective midcomponents, or both blend and midcomponent had hardness equivalents <17.

Averaged across environments, blends exceeded midcomponents in mean diameter standard deviation (SD), a measure of kernel size nonuniformity (SD of 0.455 vs. 0.441, respectively; $P = 0.0002$). The three blends that combined NC Neuse and Roane had greater nonuniformity than their respective mid-

components (NC Neuse/Roane, McCormick/NC Neuse/Roane, and NC Neuse/Roane/Tribute; data not shown, $P \leq 0.02$ in all cases). NC Neuse had a larger mean kernel diameter than McCormick or Roane (Table 5). At each Kinston and Plymouth trial individually, mean blend diameter SD exceeded mean midcomponent SD ($P \leq 0.043$ in all cases). Within environments, there were 11 blends that exceeded their respective midcomponents in diameter nonuniformity, all but one involving McCormick or NC Neuse ($P \leq 0.04$ in all cases), and one blend that had greater diameter uniformity than its midcomponent (P26R12/USG 3209 in Kinston 2005, $P = 0.052$).

For falling number, a measure of sprouting tolerance, the desired range is ≥ 350 s (Souza, 2007), and means for all pure cultivars in our experiment exceeded that threshold (Table 5). Across environments, blends and midcomponents did not differ significantly in falling number either as a whole (blends vs. midcomponents, $P = 0.89$) or in the comparisons of individual blends to their respective midcomponents (data not shown). For environments individually, mean blend falling number was higher than mean midcomponent falling number at Kinston in 2006 ($P = 0.054$), and lower than mean midcomponent falling number at Plymouth in 2005 ($P = 0.045$); all values were ≥ 395 s. Among four environments (Kinston 2006, Plymouth 2005, Plymouth 2006, and Salisbury 2006), there were a total of five blends with falling number significantly higher, and two significantly lower, than their respective midcomponents. All values were >350 s except one at Kinston 2006 (the McCormick/USG 3592 blends had 413 s, and its midcomponent 339 s).

The desired range of flour protein from soft wheat is 80 to 100 g kg⁻¹ for pastry flour, and 90 to 140 g kg⁻¹ for cracker and export flour (Souza, 2007). Across environments, mean protein content was 101 to 115 g kg⁻¹ for all entries (data for pure cultivars in Table 5), and as a whole blend protein did not differ from midcomponent protein ($P = 0.10$). One blend, AGS 2000/P26R12/USG 3209, had lower protein content than its midcomponent (104 and 107 g kg⁻¹, respectively) across environments ($P = 0.019$). Within environments, protein content of blends as a whole differed from midcomponent protein content as a whole only at Kinston in 2006. At that experiment, pure cultivars had 3.2 g kg⁻¹ higher protein content than blends ($P = 0.005$). Four blends differed significantly in protein content from their respective midcomponents in individual environ-

Table 6. Mean percentages of components† in North Carolina wheat blend plots in which tiller counts differed significantly ($P \leq 0.05$) from the 1:1 or 1:1:1 planted percentages.‡

Blend	Salisbury		Kinston		Plymouth		Mean	
	2005	2006	2005	2006	2005	2006	2005	2006
AGS2000/P26R12	56:44	43:57	57:43			43:57	53:47	45:55
AGS2000/USG3209	57:43		56:44	39:61		57:43	54:46	
McCormick/Roane	43:57	–		–	55:45	–		–
P26R12/USG3209				59:41		41:59		
Tribute/USG3592		–	44:56	–		–		–
AGS2000/P26R12/USG3209	46:24:31		43:26:31	23:46:32		21:32:47	40:27:33	29:38:34
McCormick/NC Neuse/Roane		–		–	39:34:27	–	37:35:28	–
NC Neuse/Roane/Tribute		–	40:30:30	–		–	38:30:32	–

† Percentages listed in the same order as components in the first column; for example, in Salisbury in 2005, the mean percentages of AGS2000 and P26R12 in the blend of AGS2000/P26R12 are 56 and 44%, respectively.

‡ In blank cells, the percentages of tillers did not differ significantly from equiproportional. In cells with dashes, components could be distinguished. When data were averaged for those four blends across both years, there were no significant divergences from equiproportionality: AGS 2000/P26R12, AGS 2000/USG 3209, P26R12/USG 3209, and AGS 2000/P26R12/USG 3209.

ments: one in Kinston 2006, one in Plymouth 2005, and two in Salisbury 2006. In all cases, blend protein was within the range of the pure cultivar protein contents in the test.

Tiller Counts

On average, blends retained their equiproportional composition in about half of environments (Table 6). Blends of early-maturing cultivars had more departures from equiproportionality in 2005, where AGS2000 dominated both cultivars with which it was mixed. These departures did not seem to be due to differences in resistance to wheat spindle streak mosaic virus and wheat soilborne mosaic virus; P26R12 and USG 3209 are resistant or moderately resistant to both viruses, while AGS 2000 is moderately susceptible (Weisz and Maxwell, 2006).

A comparison of Tables 2 and 6 shows that higher tiller number of a particular cultivar in a blend was not consistently associated with higher yield of that cultivar grown as a pure stand. For example, P26R12 outyielded AGS2000 and USG3209 in Kinston and Plymouth in 2006, yet P26R12 tillers comprised a significantly disproportionate share of blends involving P26R12 in only three of the six cases. P26R12 has “good” Hessian fly resistance, while AGS2000 has a “good/fair” rating, and USG3209 has a “fair” rating (Weisz and Maxwell, 2006).

DISCUSSION

To our knowledge, this is the first report of a multienvironment field experiment with small grain blends in the eastern United States. Averaged across environments, blends outyielded their midcomponents, even while pressure from foliar diseases was nonexistent to moderate in all environments. When environments were considered individually, blends significantly outyielded midcomponents only in Plymouth in 2005. Our results suggest that in the southeastern United States, blends may have a small positive yield impact under conditions of low to moderate disease severity. Theoretically, the mean yield advantage of blends should increase with more severe epidemics of foliar diseases if blends have components with complementary resistance characteristics.

Two blends significantly outyielded their respective midcomponents across environments. One of these, the NC Neuse/USG 3592 blend, paired two cultivars that diverged

for maturity, plant height, yield potential, and disease resistance (Table 1; Weisz and Maxwell, 2006). NC Neuse has late maturity, medium stature, multiple disease resistance traits, and average yield, while USG 3592 is medium-maturing and tall, yields above average, and is susceptible to powdery mildew, Hessian fly, and Fusarium head blight (Weisz and Maxwell, 2006). This blend ranked in the top five entries (Table 2, Fig. 1).

The other blend that outyielded its midcomponents across environments, McCormick/NC Neuse/Roane, consisted of cultivars with more similar maturities and plant heights (Table 1). According to state extension recommendations, McCormick and Roane are below-average yielding cultivars (Weisz and Maxwell, 2006). The blend of those two cultivars with NC Neuse ranked only slightly above average among all entries for yield. A blend may outyield its midcomponent, but it will be unlikely to attract grower interest if it does not perform well relative to other entries. For that reason, it is likely necessary that each commercially viable blend have at least one component ranked above average for yield in state variety trials.

In the top quartile of entries, blends yielded more stably than pure cultivars across our experimental locations. In general, stability measures should be calculated from more than a few environments (Becker and Leon, 1988), and so our finding of greater yield stability among blends in six environments must be considered with caution. It is, however, consistent with one of the main reasons that blends are grown, namely to buffer yield against unpredictable stresses across diverse environments. The two yield-stability indices that were used did not agree on the rankings of all entries. However, both models indicated that of the five highest-yielding entries in the experiment, the three blends (AGS 2000/P26R12, NC Neuse/USG 3592, and AGS 2000/P26R12/USG 3209) were more yield-stable than the two pure cultivars (P26R12 and USG 3209). Of course, the top-yielding blends should be tested at a wider variety of sites before making recommendations for commercial production.

Blends were least advantageous in Salisbury, which is located in the west-central Piedmont region of North Carolina, and more advantageous in the eastern Coastal Plain and Tidewater sites of Kinston and Plymouth. As the foliar diseases common to Kinston and Plymouth were relatively mild in our tests, the reasons for this result are not obvious. Perhaps host heterogeneity was beneficial in reducing marginal yield effects of foliar disease epidemics. Salisbury was the only site at which two blends were actually outyielded by their midcomponents. This suggests that Piedmont growers who experiment with blends should exercise particular caution.

Small plots did not demonstrate a blend advantage, while nearby large plots did. The factors contributing to the overall blend advantage in the larger plots, such as disease reduction and compensation, evidently had lesser effects in the smaller plots. This result is consistent with the findings of other researchers (Mille et al., 2006; Wolfe, 1985; Zhu et al., 2000). It suggests that blend efficacy must be evaluated at some minimum plot size, and blends found to be advantageous at that scale should also be tested over larger areas.

It is unclear why one blend, McCormick/Roane, had a lower test weight than its midcomponent, as one would not expect test weight to be influenced by blending. This blend also yielded below the average of entries in the trial, and would be unlikely to be recommended for commercial cultivation.

For the quality traits that were evaluated, blends performed on the whole similarly to midcomponents, as expected. Where differences were significant, blends were generally advantageous or the difference was inconsequential. The exception was kernel diameter uniformity, a trait preferred by wheat millers (Souza, 2007). Growers marketing grain for flour milling may wish to avoid blending especially small-seeded with especially large-seeded cultivars. Further research is needed to identify the effects of host heterogeneity on milling and baking quality traits.

In conclusion, it appears that some blends may be of at least modest assistance to southeastern U.S. wheat growers trying to attain consistently high yields. Wheat production in this region is challenged by many different biotic and abiotic stresses; for any given production season, it is impossible to reliably predict the likelihood of each stress at variety selection time. Blends may help to reduce risk. Further testing in more environments is warranted to identify the best blends for specific zones and to determine blend effects on yield under a wider range of disease intensities.

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