Residue Management, Seed Production, Crop Development, and Turf Quality in Diverse Kentucky Bluegrass Germplasm

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ABSTRACT

Field burning has traditionally been used to stimulate Kentucky bluegrass (*Poa pratensis* L.) seed production, but air quality issues are making this practice untenable. Our objectives were to determine agronomic and crop developmental responses of 45 diverse Kentucky bluegrass entries under burned, mechanically removed, and residue-retained management systems, assess the scope for improving yield under nonthermal residue management, and relate seed yield and turf quality factors. Compared with burned treatments, yield was reduced 27% when residue was mechanically removed from plots, and 63% when residue was retained. Higher yield was promoted by a long heading-to-anthesis period, a relatively short anthesis-to-harvest period, and an early harvest date (maturity). Although both seeds per panicle and fertile panicles per square meter were positively correlated with yield, lower yield with nonthermal residue management was closely associated with panicles per square meter. For six of the 15 highest-yielding entries, no significant difference was found between yield in the burned and residue-removed treatments, showing the dependence of yield on genotype under different residue management systems. Turf quality was negatively correlated with yield ($r = -0.48$, $P < 0.01$, $n = 44$) and seeds per panicle ($r = -0.55$, $P < 0.01$, $n = 44$). However, panicles per square meter were not significantly correlated with turf quality, so indirect selection for yield through genotypes with high panicles per square meter in the absence of high seeds per panicle should have minimal impact on turf quality. Sufficient variation for seed production appears available to encourage development of germplasm for nonthermal management systems.

KENTUCKY BLUEGRASS seed production in the USA is located primarily in the states of Washington, Idaho, and Oregon (Ensign et al., 1989). Traditionally, seed production management practices have included open-field burning after harvest to remove residue and stimulate seed production the following year. Although perennial grass fields provide excellent erosion control and other benefits to soil and environment (Canode and Law, 1977), air quality issues associated with smoke from burning fields is a major public concern. A near complete ban on burning Kentucky bluegrass seed production fields has been implemented in Washington State. Field burning Kentucky bluegrass fields is regulated in Oregon, and increasingly regulated in Idaho. The lower seed production and increased costs associated with nonthermal residue management is threatening the traditional Kentucky bluegrass seed production industry in the Pacific Northwest.

Kentucky bluegrass usually exhibits a sharp reduction in seed production unless crop residue is removed. Canode and Law (1977) found that yield reductions ranged from 40 to 80%, depending on row spacing. Mechanical removal of straw was less effective at promoting yield than open-field burning. This response is consistent with other reports on the effect of residue on seed production (Hickey and Ensign, 1983). The yield response also varies depending on the amount of residue removed, with more complete removal conducive to higher yield (Hickey and Ensign, 1983). Chastain et al. (1997) reported that Kentucky bluegrass seed yield could be maintained without field burning with near complete straw removal and reduced stubble height. Lamb and Murray (1999) found that the yield response to residue was cultivar dependent, and suggested that yield for short, small-seeded cultivars producing modest amounts of aboveground biomass could be sustained under a mechanical residue removal system.

Kentucky bluegrass is a perennial, facultative apomictic species (Huff and Bara, 1993). As a result, it is difficult to breed using classical techniques. But once a desirable, highly apomictic genotype is identified, asexual reproduction allows efficient genetic maintenance of desirable phenotypes. The difficulties are in finding high-seed-yielding types with superior turf characteristics (Bashaw and Funk, 1987). Numerous cultivars have been developed with excellent turf quality, but were never marketed because of poor seed yield. On the other hand, cultivars with high seed yield but poor turf quality are also difficult to market (van Wijk, 1985).

To understand the genetic potential for improving seed production under nonburned residue management, studies are needed with highly diverse Kentucky bluegrass accessions. The National Plant Germplasm System (NPGS) collection currently has >350 Kentucky bluegrass accessions, making an in-depth study of all accessions under different residue management systems prohibitively difficult and expensive. However, study is possible using a core collection, a much smaller number of accessions representing the majority of the diversity in the total NPGS collection. A core collection developed from agronomic attributes is available for the Kentucky bluegrass collection (Johnston et al., 1997, Johnson et al., 2002). The objectives of this study were to use the Kentucky bluegrass core collection, additional selected accessions, and cultivar checks to (i) determine agronomic and crop developmental responses of diverse germplasm under three different residue management systems, (ii) assess the scope for improving yield in Kentucky bluegrass under nonthermal residue management

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Abbreviations: HI, harvest index; NPGS, National Plant Germplasm System.

systems, and (iii) relate seed production to turf quality factors.

MATERIALS AND METHODS

An initial evaluation of 228 Kentucky bluegrass accessions and 17 check cultivars from the Western Regional Plant Introduction Station, Pullman, WA, was completed for 17 agronomic factors on replicated 1-m rows in 1994-1995 (Johnston et al., 1997). This represented all available accessions in the USDA collection at that time with germination 70% or greater. From that study, a core collection was developed using Ward's cluster analysis (SAS Institute, 1994) to include 22 accessions representing the diversity within the collection (Johnston et al., 1997). An additional 16 PI accessions with high yield and high potential turf quality based on color and texture were also selected from the initial study by Johnston et al. (1997). Subsequent taxonomy studies reveled that two of the 22 core collection entries were not *Poa pratensis* (Johnson et al., 2002). Those misidentified accessions were therefore omitted from the analysis, leaving 45 total entries. Thus, the 45 total entries in this study represented three different groups: the core collection (20 entries), the selected PI accessions described above (16 entries), and the cultivar checks (nine entries).

Seed Production Evaluation

Field plots were established at the Washington State University Turfgrass Research Area at Pullman, WA, on 19 June 1996. Seeds were mixed with rice (*Oryza sativa* L.) hulls at a ratio of 2:1 hulls to seed, and drilled with a single-row planter to a depth of 6 mm at a rate of 4.5 kg ha^{-1}. The soil was fine-silty, mixed, mesic, Pachic Ultic Haploxerolls. Each year, 120 kg ha^{-1} N was broadcast in mid-October as ammonium sulfate [$(NH_4)_2SO_4$ (21-0-0 N-P-K)]. Irrigation, weed control, and other agronomic factors were optimized. The experiment was randomized in complete blocks with a split-plot arrangement and three replications. The main plots were the three residue treatments, arranged in strips, and the subplots were the 45 germplasm entries. Each strip consisted of three treatments: residue retained, residue removed (similar to the current grower practice of baling), and residue burned. Each of the 45 germplasm entries were planted within and perpendicular to the strips in an area 1.2 m wide and 6.4 m long, and at a row spacing of 0.18 m. The germplasm entries were arranged side by side and spaced 0.6 m apart. The subplot arrangement across each residue treatment strip resulted in plots 1.2 by 2.1 m, representing each residue × entry treatment combination.

Plots were periodically irrigated during the summer of 1996 and harvest was completed on each subplot in 1997. For harvest, plots were cut with a sickle mower to a height of 60 mm, gathered in cloth bags, dried, and weighed. Harvested material was threshed in a plot combine setup in a stationary position near the plots. For the plots designated as residue retained and burned, the residue from the thresher was collected in bags and spread back on the same germplasm entry plots from which they were harvested. The seeds were debearded by processing through a hammer mill and screened through 2.4-mm diam. holes. The debearded seed was then cleaned in an air-screen cleaner. Each sample was processed through the air screen cleaner three times to obtain clean seed, which was weighed for calculating yield per plot.

On 12 Aug. 1997, field burning was completed on designated plots. For the residue-removed treatment, most residue was removed with the harvest procedure described above, but a final raking was completed on 12 Aug. 1997. This established the residue treatments for the 1998 seed production season and was repeated on 8 Sept. 1998 to establish the 1999 residue treatments.

In the spring and summer of 1998 and 1999, the following data were collected from each plot: days to heading (from 1 January), days to anthesis, days to harvest, aggressivity (aboveground rhizomatous spread), leaf habit, panicle height at harvest, aboveground biomass, seed yield, harvest index (HI), average weight per seed, seeds per panicle, and panicles per square meter. Aggressivity and leaf habit were rated on a 1-to-9 scale, with 9 equaling the most lateral spread between rows and the most vertical leaves, respectively. The ratings were taken on 27 May in 1998 and 1999. Aboveground biomass and seed yield were determined by cutting each plot to a height of 60 mm with a sickle mower, bagging, drying, threshing, cleaning, and weighing as described above for 1997. Harvest index was calculated as clean seed yield divided by total aboveground biomass. Average weight per seed was determined by counting and weighing 100 seeds from each plot. Seeds per panicle were determined by randomly sampling and cleaning 20 panicles per plot before harvest, counting the number of seeds, and dividing by the number of panicles. A yield component equation (yield g m^{-2} = average weight per seed × seeds per panicle × panicles m^{-2}) was used to calculate fertile panicles per square meter. Data were analyzed using general linear models as outlined in SAS/STAT User's guide (SAS Institute, 1994). The variance for each factor analyzed was partitioned into blocks, residue treatment, entries, years, and associated interactions. The years were repeated measures. The model was fixed so statistical inferences apply only to the specific treatment combinations and location described. Fisher's F test at $P < 0.05$ was used to determine treatment differences and the LSD at $P < 0.05$ was used for multiple comparisons.

Partial coefficients of determination (R^2) were calculated as the ratio of the sum of squares of a given treatment factor to the total sum of squares (Neter et al., 1996). This gave the proportion of variation explained by residue, entry, year, and associated interactions. Pearson's linear correlation was also completed among development and seed production factors.

For each of the three groups (core, PI selections, and checks), data for the 12 attributes or variables describing development and seed yield were used in canonical discriminate analysis using the SAS CANDISC procedure (SAS Institute, 1994). The CANDISC procedure summarizes differences among classes, in this case the core, PI selections, and check groups, by deriving linear combinations of the quantitative variables or attributes (canonical variables). The means of the canonical variable scores for each group were determined for the first and second canonical variables, and a 95% confidence interval was calculated for each of the group means.

Turf Evaluation

Turf quality was evaluated in plots adjacent to the crop production experiment described above and on the same entries. On 11 Sept. 1996, entries were planted in randomized complete blocks with three replications at a rate of 11 g seed per square meter in 1.2- by 1.5-m plots. Ammonium sulfate (21-0-0) fertilizer was broadcast at 50 kg N ha^{-1} the first week in May, July, August, and October during each growing season in 1997 through 1999. The study was irrigated weekly with ≈35 mm of water and mowed once per week at a 38-mm height.

Turfgrass quality, spring green-up, color, and leaf texture were rated using National Turfgrass Evaluation Program methods (http://www.ntep.org/). Turfgrass quality was rated

Table 1. Summary of the R^2 values (percentage variation explained) and significance resulting from analyses of variance for 12 factors measured in 1998 and 1999 at Pullman, WA, under three residue management treatments (removed, retained, or burned) on 45 Kentucky bluegrass germplasm entries.

		Treatment effects						
Attributes	**CV**	**Year**	**Residue**	**Entry**	**Year × residue**	**Year × entry**	**Residue × entry**	**Year × residue × entry**
Days to heading†	1.1	25.6**	2.9**	62.7**	0.1*	3.2**	0.7**	0.3ns‡
Days to anthesis†	0.8	36.8**	0.1*	51.3**	0.1ns	6.3**	0.5**	0.4ns
Days to harvest†	0.4	13.4**	0.4**	67.9**	0.1**	14.9**	0.8**	0.8**
Leaf habit§	2.2	0.1ns	<0.1ns	77.6**	<0.1ns	6.9**	0.2ns	0.2ns
Aggressivity§	7.2	2.2ns	1.5**	70.1**	1.5**	4.9**	1.2*	1.2*
Panicle height	8.5	13.2*	0.4ns	69.2**	1.5**	3.3**	1.9**	1.1*
Biomass	22.0	4.5ns	2.6*	56.4**	0.6ns	5.6**	3.1**	2.6**
Seed yield	39.2	5.4*	15.1**	38.4**	<0.1ns	6.7**	8.1**	2.1ns
Harvest index	43.6	27.7**	10.1**	20.5**	<0.1ns	11.2**	4.1*	2.8ns
Weight per seed	8.8	2.4ns	0.5ns	53.4**	0.5*	5.3ns	3.4ns	3.4ns
Seeds per panicle	31.7	8.3*	5.1**	47.1**	1.2*	4.5*	4.0*	2.5ns
Panicles m^{-2}	52.8	12.5*	18.6**	17.5**	0.1*	7.1**	6.9**	3.9ns

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

† Days from 1 January.

‡ ns = not significant.

§ Leaf habit and aggressivity were rated on a 1 to 9 scale with 9 the most upright and the most aggressive.

during the last week of each month from April through October and monthly values were averaged to determine seasonal turf quality. Turfgrass quality was estimated visually on a scale of 1 to 9 (1 = dead and 9 = maximum quality), integrating factors such as turf color, leaf texture, and turf density. Spring green-up was rated in mid-April, and color and leaf texture in late July each year. Spring green-up is a relative index of when growth resumes after winter and is rated on a scale of 1 to 9 (1 = dormant and 9 = entirely nondormant and green). Color was also rated on a 1 to 9 scale (1 = light green and 9 = dark green color) as was leaf texture (1 to 9 with 1 = coarse and 9 = fine). Analysis of variance was completed using SAS general linear models. The variation was partitioned into blocks, years, accessions, and associated interactions. The years were repeated measures. As with the crop production experiment, the statistical model was fixed. Fisher's F test at $P < 0.05$ was used to determine treatment differences and the LSD at $P < 0.05$ was used for multiple comparisons. Pearson correlation was completed among treatment means.

RESULTS AND DISCUSSION

Analyses of Variance

Factors associated with crop development, such as days to heading, anthesis, and harvest, had low CV values (Table 1). Factors associated with biomass and seed production tended to have high CV values. Thus, the precision in measuring developmental factors was generally higher than for production factors. Nevertheless, all attributes were significant for at least one treatment effect or interaction (Table 1). The R^2 values for the germplasm entries accounted for the largest portion of the variation except for HI and panicles per square meter. For eight of the 12 attributes, >50% of the variation was associated with entry effects (Table 1). In some cases, such as the residue effect for days to anthesis, the error term was small enough that the treatment effect was significant even when it represented only a small fraction of the total variation. Generally, residue treatments explained a smaller portion of variation than other main effects, but panicles per square meter were an important exception (Table 1). Panicles per square meter had the highest R^2 of any treatment factor associated with the residue effects, and reduced panicle number was a key factor associated with lower seed yield in nonthermal treatments (Table 2).

The only factor that was significant for all treatment effects and interactions was days to harvest (Table 1),

Table 2. Means for three residue management treatments for 45 Kentucky bluegrass entries averaged across 1998 and 1999 at Pullman, WA.

	Residue treatment			
Attributes	**Retained**	**Removed**	**Burned**	**Mean**
Days to heading†	127.3a‡	124.7b	123.8c	125.3 (4 May)
Days to anthesis†	148.5a	148.0b	148.0b	148.2 (27 May)
Days to harvest†	182.5a	182.3b	181.7c	182.2 (30 June)
Leaf habit§	6.1a	6.1a	6.1a	6.1
Aggressivity§	6.0a	6.3b	5.9a	6.1
Panicle height, cm	67.3a	70.3a	70.3a	69.3
Biomass, g m^{-2}	335.5a	425.6b	390.1ab	383.8
Yield, g m^{-2}	23.4a	46.4b	63.2c	44.3
Harvest index	0.09a	0.13b	0.17c	0.13
Weight per seed, mg	0.31a	0.31a	0.31a	0.31
Seeds per panicle	258.7a	197.6b	202.5b	219.7
Panicles m^{-2}	378.5a	780.6b	1095.5c	751.5

† Days from 1 January.

‡ Means within a row with different letters are different at $P < 0.05$ using the LSD.

§ Leaf habit and aggressivity were rated on a 1 to 9 scale with 9 the most upright and the most aggressive.

Table 3. Turf quality and yield of Kentucky bluegrass germplasm grown under three residue management treatments in 1998 and 1999. There were three groups of entries, a core collection, a group previously selected for high yield and turf quality, and cultivar checks. Turf quality and yield were obtained on separate plots at a single location at Pullman, WA.

Entry	Group	Turf quality†	Mean seed yield‡	Residue treatment mean seed yield		
				Retained	Removed	Burned
			g m^{-2}			
PI 440608	selection	4.8	114.0	62.5a§	103.2b	176.4c
PI 230132	selection	5.2	112.3	55.0a	119.2b	162.7c
PI 368241	core	5.0	106.9	56.4a	127.3b	137.1b
PI 314734	selection	5.2	79.6	29.2a	94.0b	115.7c
PI 303058	selection	5.0	75.8	41.1a	87.6b	98.7b
PI 539059	selection	5.3	74.5	50.3a	84.5b	88.6b
PI 346021	selection	4.6	71.7	43.8a	75.0b	96.3c
PI 226667	selection	5.2	69.5	30.4a	63.0b	115.2c
PI 229721	core	5.4	62.5	23.1a	62.1b	102.4c
PI 349195	selection	4.9	60.0	31.0a	68.3b	80.8b
PI 499557	selection	5.0	59.6	29.4a	53.1b	96.3c
Kenblue	cultivar	5.3	58.8	33.4a	64.4b	78.7b
PI 349188	selection	5.9	57.2	35.8a	62.1b	73.5b
PI 505898	core	5.5	55.7	28.7a	55.9b	82.3c
Monopoly	cultivar	5.5	52.4	27.3a	54.4b	75.6c
PI 539057	core	5.7	51.3	27.2a	46.7a	80.1b
Park	cultivar	5.5	48.3	16.2a	57.1b	71.6b
Victa	cultivar	6.2	42.4	18.7a	52.7b	55.8b
PI 303053	core	5.5	41.7	24.6a	39.8a	60.7b
PI 371775	core	6.0	40.5	23.9a	46.1b	51.4b
PI 237282	core	5.0	39.9	19.6a	39.5a	60.6b
PI 349178	core	6.1	38.9	23.9a	38.4ab	54.4b
Mystic	cultivar	5.9	37.4	17.3a	29.0a	66.1b
Midnight	cultivar	7.2	36.0	23.1a	43.7a	41.3a
Dawn	cultivar	5.9	34.3	23.0a	33.3ab	46.7b
PI 303056	selection	5.9	33.9	16.7a	45.2b	39.7b
PI 204491	core	5.1	31.0	12.8a	24.5a	55.6b
PI 286381	core	5.9	30.0	12.1a	31.6ab	46.3b
PI 227381	selection	4.7	28.6	9.0a	15.0a	61.9b
PI 298098	selection	5.4	27.3	12.9a	32.9ab	36.2b
Julia	cultivar	6.1	27.3	18.0a	27.9a	35.9a
PI 349223	core	5.4	25.3	12.5a	28.0ab	35.4b
PI 349225	core	5.0	24.6	18.3a	26.2a	29.4a
PI 372741	core	5.2	23.7	13.4a	18.9ab	38.8b
PI 206725	core	5.4	23.5	9.0a	24.6ab	36.8b
PI 372738	core	4.5	23.2	15.8a	17.1ab	36.8b
PI 371769	core	6.2	22.7	15.1a	17.7a	35.3a
PI 349220	selection	5.6	21.9	12.3a	26.6a	26.8a
Eclipse	cultivar	6.0	21.4	16.1a	24.3a	23.8a
PI 372742	selection	5.4	21.2	15.8a	21.7a	26.3a
PI 371768	selection	6.6	19.8	14.5a	23.8a	21.1a
PI 371771	core	6.3	10.6	5.8a	15.5a	10.6a
PI 574523	core	6.6	8.1	2.6a	13.4a	8.2a
PI 349160	core	6.2	5.5	3.6a	6.8a	6.0a

† Means of turf quality for each entry averaged across 3 yr (1997–1999) had an LSD0.05 of 0.29. Turf quality was rated on a 1 to 9 scale with 9 = maximum.

‡ Means of yield for each entry averaged across 2 yr (1998–1999) and residue treatments had an LSD0.05 of 26.6 g m^{-2}.

§ Means within a row with different letters are different at $P < 0.05$. The LSD0.05 for these comparisons was 20.9 g m^{-2}.

which was consistently modified by year, residue, and entry combinations. The factors with the fewest significant effects were leaf habit and weight per seed. For those factors, the majority of the variation was associated with entries (Table 1). In fact, every attribute had highly significant effects for entries, suggesting a high level of genetic variation within this germplasm set. As expected, crop development and seed production factors for entries were modified by the year grown. This was shown by the entry × year interactions, which were significant for every attribute except weight per seed. The entry interaction with residue was significant for 10 of the 12 attributes (Table 1), showing that entries had a wide range of responses to residue, with some entries yielding much better than others under nonburned residue treatments (Table 3).

The significant interactions were associated with the magnitude of a given response rather than its direction. That is, even though the relative ranking changed somewhat from one year to the next, a high-yielding accession in 1998 was usually high yielding in 1999. To illustrate, the linear correlation coefficient was $r = 0.78$ ($P < 0.01$, $n = 132$) between entry yield in 1998 and entry yield in 1999, showing that the direction of the yield response was consistent across years. And indeed, all correlations between the same factors measured in 1998 and 1999 were always positive and highly significant. This illustrates that averages of data for main effects are informative even when significant interactions occurred.

Group Effects

The first canonical function explained 66% of the total variation, and the second function explained the remaining 34% of the variation. The canonical functions distinguished the selected PIs, the core collection, and

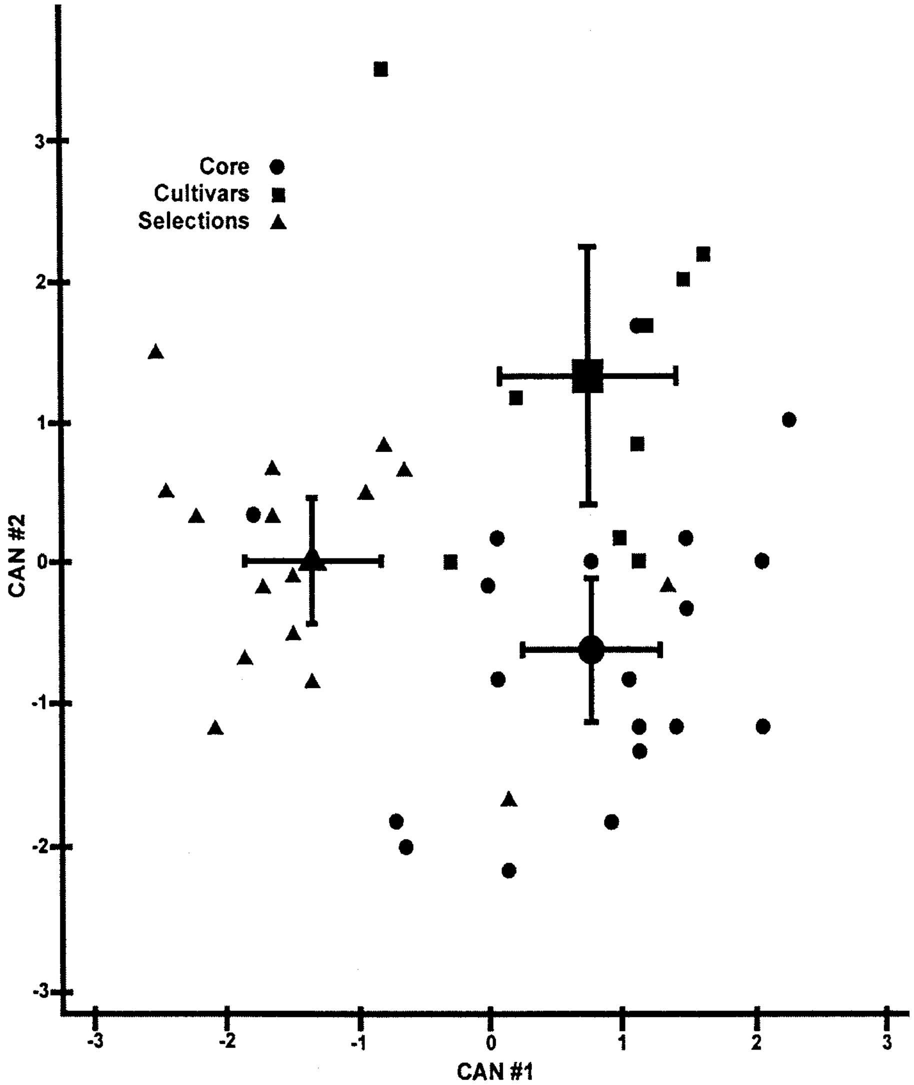

Fig. 1. Plot of variables resulting from the first (CAN #1) and second (CAN #2) canonical functions for three groups of Kentucky bluegrass based on 12 crop developmental and production attributes. The large symbols represent the mean for each group and the bars are the 95% confidence intervals.

check cultivar groups (Fig. 1). This separation is not surprising, given that the three groups originated from distinctly different processes. That is, the PI selections were picked for yield and potential turf quality from the initial Johnston et al. (1997) evaluation study, the core collection was developed using cluster analysis and represented as much diversity as possible, and the cultivars were developed by various breeders selecting for desirable attributes. Overall, the Kentucky bluegrass gene pool would be expected to be more closely represented by the core group than the cultivar or selection groups. This is because the core collection, as a result of cluster analysis, represented as much diversity as possible regardless of phenotype. The process of phenotype selection of the selected PIs and cultivars should concentrate desirable types away from the center of the wider gene pool.

The standardized canonical coefficients showed that days to heading and days to anthesis had the most influence on Canonical Function 1, and seeds per panicle and panicle height had the most influence on Canonical Function 2. Canonical Function 1 was most important in separating the selections from the cultivar checks and the core collection (Fig. 1). Since the first canonical function gave nearly the same mean for the core and the cultivar checks, the second function was critical for distinguishing those two groups (Fig. 1). Compared with the core collection, the selected PIs had significantly higher seed yield, showing that selection for higher-yielding accessions in previous evaluation work (Johnston et al., 1997) generally resulted in higher yield in these subsequent tests. The selection group also had fewer days to harvest, more upright leaf habit, and more seeds per panicle than the core collection, all attributes associated with high-yielding entries. Compared with the cultivar checks, the core collection had fewer days to heading and anthesis, but no other factor was significantly different. Thus, the core and the cultivar check groups were more closely associated than the core and the selection group, and this was also seen in the analysis of canonical variables (Fig. 1).

Although the groups were distinguished by the canonical discriminate analysis, one entry from the core collection was within the error bars of the cultivar group and one within the error bars of the selection group (Fig. 1). Thus, the Kentucky bluegrass core collection did contain representation from the cultivar and PI selection groups. The reverse was not true. Neither the cultivar nor selection groups were represented within the core error bars. Given the diversity of material in this study, the core group appeared to fulfill the intent of a core collection; that is, to represent as much of the diversity as possible in a limited number of accessions (Johnson and Hodgkin, 1999).

Residue Effects

When residue was retained, days to heading, anthesis, and harvest were delayed compared with the burned treatments (Table 2). Although the range among entries averaged 25 d for heading, 25 d for anthesis, and 16 d for harvest, the average number of days between residue treatments was relatively small or even fractional. Delayed crop development was also observed when residue was removed, but to a lesser extent than when residue was retained. The residue × entry interaction for days to heading, anthesis, and harvest were all highly significant (Table 1), showing that delays in development associated with nonthermal management were entry dependent. Neither leaf habit nor panicle height were affected by residue treatments, but when residue was removed mechanically, aggressivity increased, showing a tendency for greater rhizomatous spread than in either the residue-retained or burned treatments. Since there were fewer panicles in the residue-removed treatment than the burned treatment (Table 2), the increased rhizomatous spread was not associated with an increase in panicles per square meter, even though it was associated with increased vegetative biomass.

In the absence of burning, seed yield for the residue-removed treatment was 27% less than the burned treatment, and yield for the residue-retained treatment was 63% less than the burned treatment (Table 2). This finding is consistent with other reports of the effect of residue on seed production (Canode and Law, 1977; Hickey and Ensign, 1983; Chastain et al., 1997; Lamb and Murray, 1999). Although residue removal did not fully compensate for burning in our study, Chastain et al. (1997) found that the cultivars Abbey and Bristol (not included in this study) maintained seed yield without burning when straw removal was nearly complete and stubble height reduced. Lamb and Murray (1999), however, found that maintaining yield even with near complete straw and stubble removal was not possible with all cultivars they tested. In our study, the residue treatment × entry interaction was highly significant, showing that the response to residue was very dependent on the genetic material under consideration.

All yield components except weight per seed were affected by residue treatments (Table 1). On average, there were 29% fewer panicles per square meter in the residue-removed treatment, and 65% less in the residue-retained treatment than in the burned treatment (Table 2). Seeds per panicle were essentially equal between the burned and residue-removed treatments. Although yield was sharply reduced when residue was retained, seeds per panicle were actually higher in the residue-retained treatment than other residue treatments (Table 2). Thus, there was some compensation for the sharp reduction in panicles per square meter when residue was retained, but not nearly enough to overcome the fewer fertile panicles per square meter. Since seeds per panicle did not differ between the residue-removed and burned treatments, no compensation was observed for the fewer panicles in the residue-removed treatment (Table 2). Panicles per square meter was the factor most closely associated with yield differences across residue treatments.

Aboveground biomass did not differ between the residue-removed and burned treatments but trended lower when residue was retained (Table 2). Harvest index almost doubled in the burned compared with the residue-retained treatment, and the residue-removed treatment was intermediate (Table 2). Thus, the efficiency of conversion of aboveground biomass to seed was increased as more residue from the previous crop year was removed, resulting in a higher HI. The yield component most strongly correlated with HI was panicles per square meter ($r = 0.65$, $P < 0.01$, $n = 264$). There was a weaker but positive correlation between HI and weight per seed ($r = 0.22$, $P < 0.01$, $n = 264$), but seeds per panicle was negatively correlated with HI ($r = -0.40$, $P < 0.01$, $n = 264$). This suggests that the increased efficiency in conversion of biomass to seed yield, resulting in increased HI, was most closely associated with increased fertile panicles per square meter and to a lesser extent weight per seed.

Tiller development in relation to fertile panicle development and the tiller-rhizome relationship in Kentucky bluegrass is complex (Nyahoza et al., 1974; Hickey and Ensign, 1983; Sylvester and Reynolds, 1999). Hickey and Ensign (1983) found more rhizomes when residue was clipped than in burned plots. Chastain et al. (1997) reported that in two of three years, spring vegetative tillers were higher with nonthermal management than under burning. Those findings are consistent with our observation of increased aggressivity when residue was mechanically removed. But when residue was retained, aggressivity was equal to that of the burned treatment. The equal aggressivity in the residue-retained and burned treatments probably arose for different reasons. Our hypothesis is that when residue was retained, light penetration into the canopy was limited, which severely limited tillering and rhizome development of aboveground tissue during the fall and early spring. In other words, aggressivity was limited because of a general reduction in growth associated with limited light (Table 2). When residue was removed, however, that light limitation to growth was substantially removed. Growth was promoted in both the residue-removed and burned treatments resulting in comparable biomass production.

Yield was not comparable, however, as there was a shift in partitioning of dry matter resulting in higher HI, more fertile panicles, and higher yield in the burned than in the residue-removed treatments (Table 2).

Chastain et al. (1997) felt that the main effect of burning was simply to remove residue that inhibits regrowth. Hickey and Ensign (1983), however, found that burning reduced rhizome weights compared with clipping, and concluded that burning affected tiller apical control of rhizomes, resulting in more fertile tillers. More research is needed to fully understand the physiological mechanisms causing differences in the production of biomass, rhizomes, fertile panicles, and the partitioning of dry matter under different residue management systems. Nevertheless, since burning changed the partitioning of dry matter, that is, sources–sink relations, it did more than simply remove barriers to vegetative growth associated with residue (Table 2). It appeared that burning promoted tillering that led to more fertile panicles, whereas mechanical residue removal led to more rhizome production and leafy vegetation at the expense of fertile panicles.

Entry Effects

When the residue was retained, 75% of the entries yielded significantly less than the burned treatment (Table 3). With the residue-removed treatment, 43% of the entries yielded less than the burned treatment. A difference in yield among residue treatments was not detected for 25% of the entries. That absence of significant yield differences was observed among lower-yielding entries including the cultivars Midnight, Julia, and Eclipse. The two highest-yielding entries, PI 440608 and PI 230132, yielded substantially less in the nonthermal residue treatments than under burning, but because of their high yield capacity, they often yielded more when residue was retained than many of the entries when burned (Table 3). Among the top 15 high-yielding entries, 10 were from the high-yielding PI selection group identified from previous work (Johnston et al., 1997). Although burned plots tended to yield more, six of the 15 high-yielding entries showed no significant differences between the burned and residue-removed treatments. For example, a seed yield difference between the burned and the residue-removed treatment was not detected for the cultivar Kenblue or PI 349188, but yield of both entries was sharply reduced when residue was retained (Table 3). Under all residue treatments, Kenblue and PI 349188 had similar seed yield, but PI 349188 had much higher turf quality, showing the potential for combining improved turf and yield. Entries that did not differ in seed yield between residue-removed and burned management systems tended to have shorter height at harvest, fewer seeds per panicle, more panicles per square meter, and a higher HI than entries in which the burned treatment had higher yield. Others have observed significant interactions between residue and genotype or entry (Hickey and Ensign, 1983; Lamb and Murray, 1999). Our results emphasize the importance of the genotype in evaluating how yield is modified by different residue management systems. There appeared, moreover, considerable potential to identify genotypes with improved yield under nonthermal management.

The strongest correlation between a developmental factor and a production factor was between panicle height and biomass (Table 4), explaining >62% of the variation between those factors. Panicle height was also correlated with yield, biomass, and seeds per panicle, and biomass was also correlated with seeds per panicle ($r = 0.64$, $P < 0.01$, $n = 264$). Leaf habit was strongly correlated with biomass, yield, and seeds per panicle (Table 4). Thus, entries that produced high biomass and seed yield tended to be taller, with more upright leaves, and with more seeds per panicle than entries producing low biomass and seed yield. Higher biomass entries tended to be less efficient in their conversion to seed, resulting in a negative correlation between biomass and HI ($r = -0.30$, $P < 0.01$, $n = 264$). Greater stem length associated with taller entries likely added stem mass to taller entries, and this may have contributed to lower HI values. Aggressive entries also tended to produce more biomass, but they also tended to have fewer panicles per square meter, and were therefore less efficient in terms of HI.

Certain developmental periods significantly affected biomass, seed yield, and yield components. Days from heading to anthesis and days from anthesis to harvest

Table 4. Pearson correlation coefficients for production factors in relation to developmental factors for Kentucky bluegrass growing under three residue management systems in 1998 and 1999 at Pullman, WA. The correlations were completed on the mean of each year, residue, and entry combination.

	Biomass	Seed yield	Harvest index	Weight per seed	Seeds per panicle	Panicles m^{-2}
Days to heading	−0.32**	−0.12ns†	0.26**	0.18**	−0.34**	0.08ns
Days to anthesis	−0.06ns	0.16**	0.29**	0.10ns	−0.17**	0.23**
Days to harvest	−0.55**	−0.31**	0.15*	−0.05ns	−0.56**	0.01ns
Days heading to harvest	−0.07ns	−0.10ns	−0.15*	−0.14*	−0.05ns	−0.07ns
Days heading to anthesis	0.49**	0.46**	−0.01ns	−0.17**	0.36**	0.21**
Days anthesis to harvest	−0.38**	−0.42**	−0.18**	−0.06ns	−0.27**	−0.23**
Leaf habit‡	0.72**	0.51**	−0.17**	−0.11ns	0.61**	0.15*
Aggressivity‡	0.17**	−0.10ns	−0.22**	0.01ns	0.14*	−0.23**
Panicle height	0.79**	0.35**	−0.49**	−0.13*	0.70**	−0.10ns

* Significant at $P < 0.05$ with $n = 264$.
** Significant at $P < 0.01$ with $n = 264$.
† ns = not significant.
‡ Leaf habit and aggressivity were rated on a 1 to 9 scale with 9 the most upright and 9 most aggressive.

were quite strongly correlated with biomass production, seed yield, seeds per panicle, and panicles per square meter (Table 4). For days from heading to anthesis, those correlations were always positive; for days from anthesis to harvest, they were always negative. Thus, a longer period from heading to anthesis promoted yield, but so did a shorter period from anthesis to harvest. The longer heading-to-anthesis period apparently allowed time for the development of fertile panicles and seeds per panicle critical for high seed number. Moreover, a shorter anthesis-to-harvest period allowed escape from the higher temperature associated with the onset of summer. Consistent with our results, Ensign et al. (1989) found early anthesis and harvest date promoted yield in Kentucky bluegrass. The current work is the first to report the importance of a longer heading-to-anthesis period and relatively shorter period from anthesis to harvest to promote yield.

Turf Factors and Production

The correlation between turf color and turf quality was positive and strong, but turf quality was negatively correlated with spring green-up and texture (Table 5). Thus, among the factors rated, color was the turf factor most important to overall quality. Early spring green-up would be a positive turf attribute as long as overall quality was also high. However, entries that had early green-up often displayed poor overall turf quality. We hadn't expected finer leaf texture (higher ratings) to negatively correlate with turf quality and color, but several of the selected PI entries had very fine texture, yet they had poor color, and overall poor turf quality. The cultivar Victa had the lowest leaf texture rating of 4.9 but a high color (8.1) and turf quality (6.2) rating. This showed that fine texture was not essential for high quality turf. The cultivar checks as a group had a mean leaf texture rating of 6.0, which was comparable with the experimental mean of 6.2, suggesting that medium leaf texture was generally associated with genotypes with good turf color and quality.

Seed yield was significantly correlated with each of the turf evaluation factors (Table 5). Correlations with yield were positive for finer texture and for earlier spring green-up, and negative for darker color and overall turf quality. The negative correlation between turf quality and seed yield supports the conventional belief that high yield and high quality tend to be mutually exclusive (van Wijk, 1985). Nevertheless, that correlation explained only 23% of the variation between turf quality and seed yield, showing that it should be possible to combine turf quality with higher yield in certain, unique genotypes.

Weight per seed did not correlate with yield or any turf factor measured (Table 5). The entry with the highest weight per seed was the cultivar Victa at 0.40 mg, compared with the entry average of 0.31 mg. But Victa also averaged only 149 seeds per panicle, compared with an experimental average of 220, and yielded 42.4 g m^{-2}, which was near the entry average of 44.3 g m^{-2}. This illustrates a yield component compensation effect. The three highest-yielding entries (PI 440608, PI 230132, and PI 368241) had an average weight per seed of 0.30 mg, which was very close to the experiment-wide mean, but average seeds per panicle of 325, which was well above the experiment-wide mean. So unless weight per seed can be increased without compensation effects with other yield components, selection for weight per seed would not be expected to increase yield.

On the other hand, seeds per panicle and panicles per square meter were strongly correlated with seed yield (Table 5). The negative correlation between turf quality and seeds per panicle showed that high seeds per panicle was associated with poorer turf quality. Panicles per square meter, however, was not significantly correlated with turf quality or color (Table 5). As a result, indirect selection for yield with genotypes that produce high panicles per square meter in the absence of high seeds per panicle would be expected to promote high seed yield and have far less, if any, negative effects on turf quality. For example, Kenblue and PI 349188 had similar yield but PI 349188 had higher turf quality (Table 3). Kenblue averaged 276 seeds per panicle and 708 panicles m^{-2} compared with 135 seeds per panicle and 1322 panicles m^{-2} for PI 349188. Moreover, higher panicles per square meter should lead to more efficient dry matter partitioning as HI was positively correlated with panicles per square meter ($r = 0.53$, $P < 0.01$, $n = 44$). For seeds per panicle, the correlation with HI was negative ($r = -0.35$, $P < 0.05$, $n = 44$). There was also evidence that high HI was associated with superior turf color (Table 5). Perhaps the combination of higher yield and turf quality is promoted when a larger number of finer-stemmed, shorter panicles develop from more rhizomatous types, which have less capacity to support the high number of seeds per panicle observed in taller, more caespitose types.

Higher yield through panicles per square meter alone

Table 5. Pearson correlation coefficients for entry effects between seed yield and yield components, and turf and agronomic factors.

Turf factors†	Turf quality	Biomass	Seed yield‡	Harvest index	Weight per seed	Seeds per panicle	Panicles m^{-2}
Texture	−0.33*	0.32*	0.37*	−0.12ns§	−0.20ns	0.30ns	0.25ns
Color	0.67**	−0.56**	−0.40*	0.43**	0.23ns	−0.56**	−0.17ns
Spring green-up	−0.38*	0.51**	0.37*	−0.47**	−0.14ns	0.61**	−0.19ns
Turf quality	–	−0.53**	−0.48**	0.22ns	0.15ns	−0.55**	−0.26ns
Seed yield	−0.48**	0.84**	–	0.12ns	0.05ns	0.76**	0.66**

* Significant at $P < 0.05$ with $n = 44$.

** Significant at $P < 0.01$ with $n = 44$.

† Texture, color, and spring green-up were rated on a 1 to 9 scale with 9 equaling the finest texture, darkest green color, and entirely nondormant and green. Turf data were averaged across years from 1997 through 1999 at Pullman, WA.

‡ Seed yield data were averaged across years (1998 and 1999) and residue management treatment from plots at Pullman, WA.

§ ns = not significant with $n = 44$.

would not be expected to rival the yield capacity of genotypes with both high panicles per square meter and seeds per panicle. For example, the highest-yielding entries, PI 440608, PI 230132, and 368241, not only had high panicles per square meter, averaging 1399, but also high seeds per panicle, averaging 325.

Since Kentucky bluegrass is a facultative apomictic species, some sexual reproduction is possible, and potential sexual reproduction varies among genotypes (Barcaccia et al., 1997). Field-collected plant populations can contain different genotypes within a single accession, which can lead to within-accession variation. Recent observations of spaced plants of some entries from this study show considerable within-entry, plant-to-plant variation in agronomic attributes. This suggests there is scope for selecting individual plants for higher panicles per square meter from within some germplasm accessions. With such an approach, the yield capacity of germplasm with high turf quality might be improved. Conversely, perhaps genotypes with improved turf quality could be found within higher-yielding accessions. More study is needed to understand how selection using yield components such as panicles per square meter interacts with environment, yield, and turf quality factors.

In addition to the potential for utilization of existing germplasm, there is a need to expand the USDA Kentucky bluegrass collection. Johnson et al. (2002) found, using dendrograms based on both molecular and agronomic evaluations, that the majority of Kentucky bluegrass in the USDA collection fell into just a few clusters. This suggested that the diversity of the collection, while substantial, should be improved to identify additional unique types with wide adaptation and acceptable seed yield and turf characteristics. This should include additional naturalized material from the USA as well as new collections from Eurasia, where Kentucky bluegrass likely originated (Hartley, 1961). Even though new germplasm collection and evaluation is needed, and finding turf with wide adaptation and high seed yield is challenging, sufficient variation for seed production appears available to encourage development of germplasm for nonthermal management systems.

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