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Grass weed competition with bread wheat in Ethiopia: I. Effects on selected crop and weed vegetative parameters and yield components

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ABSTRACT

Competition effects of four of the predominant grass weed species in Ethiopia *(Avena abyssinica* Hoechst, *Lolium temulentum L., Snowdenia polystachya* Fresen (Pilg), and *Phalaris paradoxa* L.) on the morphological characters, grain yield, and yield components of bread wheat *(Triticum aestivum* L.) were studied in western Shewa Zone of Ethiopia. The four grass species varied significantly in their effects on wheat plant height, tillering, leaf area index (LAI), number of fertile spikes m^-2, grains per spike, spike length, thousand grain weight, straw, biomass, harvest index and grain yield. *A. abyssinica* and *S. polystachya* were the most competitive, reducing wheat morphological characters and yield components to a greater extent than *L. temulentum* and *P. paradoxa.* The reduction in wheat grain yield was linearly proportional to the square root of weed seedling density. Grass species by seedling density interaction effects were significant for most of the crop and weed characters measured, indicating a differential rate response for individual species. The reduction in wheat grain yield at the maximum weed density of 320 seedlings m^-2 ranged from 48 to 86% across the four grass species studied. The wheat yield components most affected by weed competition were number of fertile spikes m^2 and number of seeds/spike. Weed vegetative and reproductive characters (i.e., number of tillers, LAI, number of panicles, and plant height) varied markedly among species and in direct proportion with weed seedling density. Plant height and LAI appeared to be the factors most closely associated with weed competitive ability with bread wheat.

Key Words: Competition, grass weeds, wheat, yield components

RESUME

Les effets de competition de quatre des predominantes especes d'adventices en Ethiopie *(Avena abyssinica* Hoechst, *Lolium temulentum L., Snowdenia polystachya* Fresen (Pilg), et *Phalaris paradoxa* L.) sur les caracteres morphologiques, le rendement en grain, et les composantes du rendement du ble *(Triticum aestivum* L.) etaient etudies dans la zone ouest de Shewa en Ethiopie. Les effets des quatre especes d'herbes variaient considerablement sur la hauteur du ble, le tallage, l'indice de surface foliaire, le nombre d'epis fertiles m^-2, les grains par epi, la longueur de l'epi, le poids de mille grains, la paille, la biomasse, l'index de recolte et le rendement en grain. *A. abyssinica* et *S. polystachya* etaient les plus competitifs, reduisant grandement les caracteres morphologiques et les composantes du rendement en ble que *L. temulentum* et *P. paradoxa.* La reduction du rendement en grain de ble etait linealrement proportionnelle a la racine carree du taux de germination des adventices. Les effets d'interaction du taux de germination des especes d'herbes etuient signicatifs pour la plupart des characteres mesures sur la culture et sur les adventices, indiquant une difference de taux de reponse par espece individuelle. La reduction du rendement en grain du ble a la densite maximale des adventices de 320 plantes m^-2 variait de 48 a 86 % autour des quatre especes d'herbes etudiees. Les composantes du rendement en ble les plus affectees par la competition des adventices flaient le nombre d'epis fertiles m^2 et le nombre de graines/epi. Les caracteres vegetatifs et reproductifs des adventices (le nombre de tailes, l'indice de surface foliaire, le nombre de panicules, et la hauteur de la plante) varialent remarquablement parmi les especes, et en proportion directe avec le taux de germination des adventices. La hauteur de la plante et l'indice de surface folialre sont apparus etre les facteurs les plus etroitement associes avec l'habilite de competition des adventices avec le ble.

Mots Cles: Adventices, ble, competition, composantes du rendement

INTRODUCTION

Wheat *(Triticum* spp.) is the fifth most important crop in Ethiopia, both in terms of area and production. The total area of wheat production in Ethiopia is about 0.75 M ha, being divided almost equally between durum (*T. durum)* and bread wheat (*T. aestivum).* Wheat is produced both on state farms and peasant farmers' fields. The mean national wheat yield is low, ranging from 1.0 t ha^-1 for durum wheat to 1.5 t ha^-1 for bread wheat (Hailu *et al.* 1991).

Grass weeds are problematic in the wheat growing regions of Ethiopia for several reasons (Tanner and Giref, 1991). Seeds of many grass species, such as wild oat *(Avena* spp.), are difficult to separate from wheat seed. Removal of grass weeds by hand weeding a broadcast wheat crop is practically impossible during early growth stages (i.e., when yield losses occur) due to the similar morphology between grass weeds and wheat. Thus, farmers in Ethiopia tend to delay hand weeding until the weeds are distinct from wheat plants, exposing the crop to weed competition for an extended period. Chemical weed control, on the other hand, necessitates the use of relatively expensive herbicides which farmers may not be able to afford; often, grass herbicides are not readily available in Ethiopia.

Surveys have shown that *Snowdenia polystachya, Phalaris paradoxa, Lolium temulentum, Avena abyssinica, A. fatua, Bromus pectinatus* and *Setaria pumila* comprise the major problematic annual grass species in wheat growing regions of Ethiopia (SPL, 1980; Birhanu, 1985; Rezene, 1985; Tanner and Giref, 1991). The first four species have been used in the current study.

In the UK, *A. fatua* competition decreased the number of fertile tillers per plant and grains per ear of barley, and reduced individual grain size (Wilson and Peters, 1982). *Viola arvensis* depressed the grain yield of spring wheat mainly by reducing stand density, number of grains per ear, and thousand grain weight (Holzmann and Niemann, 1986). Abdul Majid and Sandhu (1984) reported that wheat under competition from *Fumaria parviflora* exhibited significantly decreased numbers of productive tillers, plant height, grains per spike and thousand grain weight.

This experiment was conducted to determine the competitive effects of varying densities of four of the major annual grass weed species in Ethiopia on bread wheat yield components, and to study the canopy and morphological characteristics of the crop-weed associations.

MATERIALS AND METHODS

Field experiments were conducted at the Plant Protection Research Centre (PPRC) of the Institute of Agricultural Research of Ethiopia during the three cropping seasons of 1992-1994. The PPRC is located at an altitude of 2225 m asl and is 125 km west of Addis Ababa (8 degrees 55' N, 37 degrees 52' E). The PPRC soil is an unclassified Vertisol. Mean annual maximum and minimum temperatures are 26.0 and 11.5 C, respectively. Mean annual rainfall is 1160 mm (measured over ten years). Specific climatic data for the three years included in this study are presented in Table 1.

TABLE 1. Climatic data at the Plant Protection Research Centre for 1992-94

	1992	1993	1994
Rainfall (mm)			
Annual	1223.8	917.8	912.0
Cropping season^a	834.9	741.5	652.0
Mean Maximum Temp. (C)			
Annual	23.9	24.7	25.3
Cropping season	22.2	19.6	23.7
Mean Minimum Temp. (C)			
Annual	8.8	10.3	11.6
Cropping season	8.2	9.2	11.5

^a: June to October, inclusive.

The experimental design used was a split-plot arrangement of a RCBD with three replications. Main plots consisted of the four grass weed species, *Avena abyssinica [Aa], Lolium temulentum [Lt], Snowdenia polystachya [Sp]* and *Phalaris paradoxa [Pp].* Eight subplots consisted of weed seedling densities (0, 5, 10, 20, 40, 80, 160 and 320 seedlings m^-2). The experimental weed densities were representative of the range commonly encountered in farmers' fields.

Germination tests were conducted for each grass weed seed sample to determine the amount of seed required to obtain the specified seedling densities in the field. Accordingly, 1.2, 1.2, 4.3, and 6.5 seeds of *Aa, Lt, Sp* and *Pp,* respectively, were needed to establish one seedling in the field. Weed seeds were sown at a rate 50% in excess of the calculated requirement to minimise the risk of poor emergence in the field. Additionally, the emergence rates of the four weed species were determined relative to the bread wheat cultivar used. Thus, to ensure that wheat and weed seedling emergence coincided, plots were hand sown with the pre-weighed amounts of *Aa, Lt* and *Sp* seed three days before wheat; *Pp* was sown ten days before wheat. Sowing dates for wheat were July 10, 5 and 9 in 1992, 1993 and 1994, respectively.

Subplots comprised 7 rows of wheat spaced at 20 cm and extending 1.6 m in length. Urea and diammonium phosphate fertilizers were broadcast at total nutrient rates of 60 kg N and 26 kg P ha^-1 and were manually incorporated into the soil prior to seeding. Bread wheat cv. K6295-4A, which is widely grown in the country and is well-adapted to the PPRC vicinity, was used as the test crop at a seed rate of 120 kg ha^-1, equivalent to 380 seeds m^-2. Wheat was sown into rows marked by hand.

Maintenance of treatments consisted of continuous hand weeding of non-target weed species and the surplus seedlings of target weeds before they reached a height of 5 cm or the two leaf stage (J. Unger, pers. comm.). A broad spectrum fungicide (triadimefon at 1.5 kg a.i.ha^-1) was sprayed across all plots to control an unidentified foliar blight on *Lt* and rust *(Puccinia* spp.) on *Aa.*

A net plot, consisting of three central rows of 1.0 m length (0.6 x 1.0 m = 0.6 m^2), was marked with pegs in each subplot; this area was used for sampling the tillering capacity of the crop and the weeds, estimating leaf area indices (LAI), and measuring yield and yield components. All wheat crop parameters were measured in each year of the trial with the exception of LAI (1994 only). Weed biomass was measured in each of the three years; weed heights and panicle or spike densities were measured in 1993 and 1994, and weed LAI was measured in 1994 only. All weed parameters were recorded from the net plot.

Analysis of variance was conducted for each measured parameter within and across seasons. Interaction means and main effect means were compared by the LSD test at the P=O.05 level.

Wheat crop and weed biomass data were simultaneously regressed on square root transformed weed.densities across the four weed species, using indicator variables to represent species (Neter *et al.* 1990). Thus, the regression analysis conformed to a model with four classes (i.e., 3 indicator variables) for the qualitative variable (representing weed species) with interactions added. The fitted regression equation was:

$$Y = b0 + b1X1 + b2X2 + b3X3 + b4X4 + b5X1X2 + b6X1X3 + b7X1X4$$

where X1 = (weed density)^1/2,
X2 = 1 for *Aa, 0* otherwise,
X3 = 1 for *Lt, 0* otherwise,
X4 = 1 for *Sp, 0* otherwise.

Each multiple regression analysis initially included all components; an iterative process was adopted, sequentially eliminating components exhibiting the least contribution to the regression sum of squares and being non-significant individually (P>0.05). Ultimately, only those components with significant (P<0.05) contributions to the multiple regression were retained for each regression model.

RESULTS AND DISCUSSION

As an indication of the precision of trial establishment, wheat seedling density (data not shown) exhibited no differences due to year, or treatment main or interaction effects: mean density was 220 wheat seedlings m^-2 with an associated C.V. of 4.63%.

The results of the combined ANOVA for wheat crop parameters are presented in Table 2. Although year effects and interactions between years, species and/or density effects exhibited significance, such effects arose from slight relative differences in the magnitude of responses over seasons and not from shifts in treatment rankings (i.e., there were no crossovers across years). The stability of treatment effects upon crop parameters across seasons was evident from the partitioning of total variance within the combined ANOVA: taking wheat grain yield as an example, the sums of squares (SS) attributable to weed species, density and species by density interaction accounted for 12.2, 79.3 and 5.8% of the total

SS; the corresponding interactions with seasons accounted for 0.5, 0.3, and 0.3% of the total SS. As a result, main treatment and interaction effects (i.e., fixed factors) exhibited high levels of significance based on the appropriate error terms (i.e., the respective interactions with year: a random factor).

TABLE 2. Results of the ANOVA on wheat crop parameters at Ambo, Ethiopia (1992-94)

	Plant height (cm)	Seeds per spike	Spikes per m^2	TKW^a (g)	Harvest index (%)	Wheat biomass (kg ha^-1)	Grain yield (kg ha^-1)
Year (Y)	NS	*	**	**	**	***	**
Weed species (S)	P<.1	**	***	**	***	***	***
S x Y	NS	***	*	P<.1	NS	***	**
Weed Density (D)	***	***	***	***	***	***	***
D x Y	NS	*	***	**	***	***	***
S x D	NS	***	***	***	*	***	***
S x D x Y	**	P<.1	***	NS	***	NS	***
Mean	99.1	24.9	282	28.6	31.9	6513	2148
C.V.(%)	1.68	5.90	5.75	2.25	7.76	6.15	5.25

*, **, ***, Significant at the 5, 1 and 0.1% levels, respectively.
When significant, each mean square for interaction with year was used as the denominator for the F-test of the corresponding fixed effect (i.e., S, D or S x D).
^a Thousand kernel weight.

The main effect of weed seedling density was highly significant for all wheat crop parameters listed in Table 2, plus wheat spike length, straw yield, LAI and test weight.

The four grass species differed significantly (Table 2) in their effects upon all measured crop parameters with the exception of plant height (P<.1); similarly, the species by density interaction effects were significant for all crop parameters except height. *Aa* and *Sp* depressed all wheat crop parameters to a greater extent than *Lt* and *Pp.* Further, the rate of decline with increasing weed seedling density was greatest for *Aa* and *Sp* for each crop parameter.

Effects on wheat yield components.

The number of fertile wheat spikes m^-2 and the mean number of tillers per wheat plant decreased markedly as weed seedling density increased (data not shown). At a given weed density, the density of wheat spikes varied across weed species, suggesting a difference in the competitive abilities of the weed species. As illustrated in Figure 1, the maximum reduction in wheat spike density at 320 weed seedlings m^-2 followed the sequence of *Sp* (59%) >*Aa* (53%) > *Lt* (42%) > *Pp* (25%). Similar to the current results, Wilson and Peters (1982) indicated that *A. fatua* competition significantly reduced wheat tillering and fertile spike production.

The effects of competition on the number of seeds per spike (SPS) and thousand kernel weight (TKW) also varied among the four weed species. The reductions in these two yield components due to *Aa* and *Sp* were similar and greater than the effect of *Lt* which, in turn, exceeded the effect of *Pp* (Fig. 1). Regarding SPS, the reductions at maximum weed density were 61, 60, 24 and 21% for *Aa, Sp, Lt* and *Pp,* respectively; the corresponding reductions in TKW were 20, 20, 15 and 11%.

Figure 1. Reduction (%) of grain yield and three yield components of bread wheat by 320 seedlings m^-2 of four grass weed species (letters indicate significance groupings at the 5% level of the LSD test)

The effects of grass species and densities on wheat yield components were similar to the overall effects on grain yield, although each yield component was affected to a lesser extent than the resultant grain yield. The results suggest that the reduction in grain yield was primarily due to a decrease in productive spikes m^-2 and grains per spike, whereas TKW was less affected (Fig. 1). In the literature, various reports on weed competition in wheat attributed yield reduction to decreases in spike numbers (Bell and Nalewaja, 1968; Cudney *et al.,* 1989; Liebl and Worsham, 1984), spike length (Burrows and Olson, 1955), TKW (Bell and Nalewaja, 1968; Wilson and Peters, 1982; Abdul Majid and Sandhu, 1984) and the number of grains per spike (Wilson and Peters; 1982; Abdul Majid and Sandhu, 1984; Holzmann and Niemann, 1986).

Wheat biomass, straw yield and harvest index were also significantly reduced by the competitive effects of the four grass species and by increasing weed density (Table 2). Researchers elsewhere reported decreased biomass and straw yield, harvest index and plant height of wheat as weed density increased (Wilson and Peters, 1982; Cudney *et al.* 1989; Wilson and Wright, 1990). In the current study, *Sp* (78%) and Aa (78%) reduced biomass yield more than *Lt* (56%) and *Pp* (40%) at the maximum weed seedling density. For harvest index (HI), the corresponding reductions were 38, 37, 13 and 12%, again demonstrating the greater competitive ability of *Aa* and *Sp.*

Weed characteristics.

The results of the combined ANOVA of measured weed parameters are presented in Table 3. The stability of treatment effects upon weed parameters across seasons was evident from the ANOVA: the SS attributable to weed species, density and species by density interaction accounted for 6.8, 84.9 and 4.4% of the total SS; the corresponding interactions with season accounted for 0.9, 0.3, and 0.8% of the total SS. Similar to the analysis of wheat crop parameters, main treatment and interaction effects were significant when compared to the appropriate error terms (i.e., the respective interactions with year).

The grass species differed significantly for all measured parameters. Increasing weed seedling density also affected the weed parameters, but at different rates for the individual species; hence, the significant species by density interactions. For example, the most competitive weed species, *Aa* and *Sp,* exhibited significantly higher biomass (Fig. 2) and LAI (Fig. 3) than *Lt* and *Pp,* particularly at the maximum density of 320 seedlings m^-2 (even though significant differences among species could be detected at the minimum density of 5 seedlings m^2). The greater productivity *of Aa* and *Sp* was reflected in the biomass production per seedling sown (data not shown); at 320 seedlings m^-2, *Sp* produced 3.56g biomass per seedling, *Aa* produced 3.51, *Pp* produced 2.53 and *Lt* produced 2.29g.

Figure 2. Biomass produced by four grass weed species at the minimum and maximum established seedling densities (letters indicate significance groupings at the 5% level of the LSD test)

Figure 3. LAI of four grass weed species at the minimum and maximum established seedling densities (letters indicate significance groupings at the 5% level of the LSD test)

The greatest number of grass infloresences m^-2 was produced by *Pp* and *Lt,* particularly at the highest seedling densities; at 320 seedlings m^'2, inflorescence densities were 567 m^-2 for *Lt,* 549 for *Pp,* 450 for *Sp* and 448 for *Aa.* The number of fertile tillers per plant for each grass species declined as seedling density increased from 5 to 320 m^-2. At the lowest density, the number of tillers produced were 8.53, 8.48, 8.15 and 11.00 per seedling of *Aa, Lt, Sp* and *Pp,* respectively; these values decreased to 1.41, 1.80, 1.39 and 1.69 at 320 seedlings m^-2. Increased plant population resulted in greater inter- and intraspecies competition for growth inputs, reducing tillering and increasing the senescence of seedlings and tillers. Since the reduction in wheat yield due to *Aa* and *Sp* competition was greater than the effects *of Lt* and *Pp,* it can be concluded that the greater tillering capacity of the latter two species is not related to the ability to compete with a wheat crop.

Plant height.

Plant height differed significantly among the four weed species (Table 3) and was probably a major factor in determining competitiveness. The height of wheat cv. K62954A was 102 cm under weed-free conditions in this study. By comparison, the maximum heights of the four grasses, exhibited under the lowest weed density of 5 seedlings m^-2, were 123 cm for *Aa,* 107 for *Lt,* 143 for *Sp*, and 105 for *Pp*; thus, the two most competitive grass weeds, *Aa* and *Sp,* were the tallest. At the maximum weed density of 320 seedlings m^-2, the four species exhibited reduced heights due to increased inter-plant competition: heights were 106 cm (-14%) for *Aa,* 100 (-7%) for *Lt*, 124 (- 13%) for *Sp* and 92 (- 12%) for *Pp*.

TABLE 3. Results of the ANOVA on weed canopy parameters at Ambo, Ethiopia (1992-94)

	Weed biomass (kg ha^-1)	Weed leaf area index^a	Weed height^b (cm)	Inflorescence density^b (no. m^2)
Year (Y)	*	-	**	NS
Weed species (S)	**	***	*	***
S x Y	***	-	***	NS
Weed density (D)	***	***	***	***
D x Y	***	-	NS	NS
S x D	***	***	***	***
S x D x Y	***	-	NS	*
Mean	4926	4.25	115	250
C.V.(%)	9.36	13.15	3.40	6.55

*, **, *** Significant at the 5, 1 and 0.1% levels, respectively.
^a: 1994 data only.
^b: 1993-94 data only.
When significant, each mean square for interaction with year was used as the denominator for the F-test of the corresponding fixed effect (i.e., S, D or S x D).

Surprisingly, plant height was the sole wheat crop parameter not exhibiting a significant weed species by density interaction (Table 2); crop heights at 320 weed seedlings m^-2 were 93 cm (-8%) for *Aa*, 94 (-8%) for *Lt*, 93 (-9%) for *Sp*, and 97 (-5%) for *Pp.* Thus, crop height did not reflect weed competition to the same extent as the wheat yield components previously discussed.

Leaf area index.

Differences in LAI [i.e., (cm^2 leaf)/(cm^2 ground surface)] were observed among the four grass species and in response to the density of weeds sown per unit area (Table 3). The LAI of wheat was affected by the same factors (data not shown).

The maximum reduction of wheat LAI to 1.595 (from 5.115) was effected by *Sp* at 320 seedlings m^-2. However, at this density, there were no significant differences in wheat LAI among *Sp* (-69%), *Aa* (-66%) and *Lt* (-55%); there was also no difference between *Lt* and *Pp* (-43%). The variation among the four weed species in reducing wheat LAI probably reflects differences in seedling growth rates, the inherent vigour of the weeds, and relative competitive abilities at early growth stages.

The greatest weed LAI was consistently produced by *Sp* and the lowest by *Lt* (Fig. 3); no significant difference was observed between *Lt* and *Pp* at any seedling density. By contrast, the number of spikes m^-2 produced by *Sp* was significantly lower than *Pp.* In principle, a greater number of tillers m^-2 is expected to increase leaf area index. However, *Sp,* due to its broader and longer leaves, had a much greater individual leaf area which contributed to the difference in LAI. Similarly, *Aa* had wider and longer leaves in comparison to *Lt* and *Pp.*

LAI is an important measure of potential photosynthetic area and, thus, of capacity for growth. The greater LAI of *Sp* and *Aa,* coupled with their taller stature, must have contributed to their greater competitive ability compared to *Lt* and *Pp.* Moreover, the leaf canopies of *Sp* and *Aa* appeared to be more effectively distributed for light interception than those of *Lt* and *Pp.* In their study of the competitive interactions of wheat and wild oat *(A. fatua),* Cudney *et al.* (1989) reported a linear decrease in wheat LAI and a corresponding increase in wild oat LAI associated with an increase in wild oat density.

Grain yield of wheat.

Competition effects on wheat grain yield varied with grass species and density (Table 2). The lowest mean wheat yields were obtained under competition from *Sp* and *Aa* (Table 4). The low yield reduction by *Pp* could be due to its slow seedling growth rate (i.e., stem elongation of wheat occurred during the tillering stage of *Pp).* This probably favoured the associated wheat, giving it a competitive advantage over *Pp.* In addition, the lower LAI and shorter stature of *Pp* compared to the other three grasses contributed to its weak competitive ability. The greater seedling growth rates, LAI, plant vigour and statures of *Sp* and *Aa,* on the other hand, contributed to the significantly lower wheat yields obtained under competitive conditions. *Lt* exhibited rapid seedling growth like *Sp* and *Aa,* but exhibited lower LAI and plant height, reducing its competitive ability with wheat. Zimdahl (1980) noted that the success of the most vigorous weed competitors was attributable to early and uniform germination ability, and the development of a large leaf assimilation surface during early seedling stages. Wilson and Wright (1990) also reported differences in competitive ability among weed species, while Wilson (1986) reported that wheat yield responses were affected more by weed species than by weed density.

TABLE 4. The effects of competition from four grass weed species at eight seedling densities on wheat grain yield (kg ha^-1) at Ambo (1992-1994)

Weed seedling density (no.m^-2)	Grass weed species				Seedling density means
	A.abyssinica	L.temulentum	S.polystachya	P.paradoxa	
0	3256 a	3176 abc	3226 ab	3233 ab	3223 A
5	3026 bcde	3033 bcde	2991 cde	3111 abcd	3040 B
10	2565 g	2852 ef	2607 g	2954 de	2744 C
20	2211 h	2658 fg	2206 h	2846 ef	2480 D
40	1556 l	2180 hi	1644 kl	2598 g	1994 E
80	1026 m	1822 jk	1017 m	2259 h	1531 F
160	700 n	1546 l	648 n	1987 ij	1220 G
320	478 o	1200 m	439 o	1685 kl	951 H
Species means	1852 C	2308 B	1847 C	2584 A	

Values followed by a common letter among the species, densities, or species by density interaction means are not significantly different at the 5% level of the LSD test.

LSD values: 187 between species means; 112 between density means; 210 between species by density interaction means.

In this study, the effects of weed densities on wheat grain yield were consistent and highly significant across the three years. Grain yield decreased from 3223 kg ha^-1 for the weed-free check to 951 kg ha^-1 at the highest weed density (Table 4).

The highly significant weed species by density interaction indicated a difference in competitive ability among the four grasses at different density levels. As shown in Table 4, 10 seedlings m^-2 of *Sp* resulted in a yield reduction equivalent to 10 *Aa,* 20 *Lt* or 40 *Pp* seedlings m^2. At the highest weed density, *Sp, Aa, Lt* and *Pp* reduced wheat grain yield by 86, 85, 62 and 48%, respectively (Table 4). Tanner *et al.* (1995) reported that the grain yield of wheat in Ethiopia was linearly proportional to the seedling density of *A. fatua;* yield reductions at 90 weed seedlings m^-2 ranged from 26 to 63% across four bread wheat cultivars. In the USA, 84 *A. fatua* seedlings m^-2 reduced wheat yields by 22% (Bell and Nalewaja, 1968).

The grain yields reported in this paper included total wheat yield; maximum effort was made to reduce losses of small grains which would have been lost during mechanical harvesting or seed cleaning. TKW showed a significant decrease as the density of each grass weed species increased. Thus, actual yield losses from weed competition under field conditions would likely have exceeded those reported here. In some cases, small seed size reduces the market value of grain; thus, an additional financial loss due to weed competition could be incurred by farmers.

Multiple linear regression analyses.

Measured crop and weed parameters were fitted to a multiple linear regression model, using the square root of weed seedling density as an independent variable and indicator variables to capture species main and species by density interaction effects (Neter *et al.* 1990). The coefficients b0 and b1 represent the intercept and slope for the *Pp* regression line; b2, b3 and b4 (when significant) sum with b0 to provide the intercepts for *Aa, Lt* and *Sp,* respectively; b5, b6 and b7 sum with b1 to give the corresponding slopes.

TABLE 5. Coefficients for the best fit multiple regression analyses for wheat crop canopy parameters and weed biomass

	Crop height (cm)	Spike index (cm)	Harvest length (%)	Wheat biomass (kg ha^-1)	Weed biomass^a (kg ha^-1)
b0	102.1	6.132	35.13	9096	1099
b1	-0.2706***	-0.0787***	-0.2499***	-215.2***	456.2***
b2	NS	NS	NS	NS	770.4*
b3	NS	NS	NS	NS	-574.2**
b4	NS	NS	1.361*	-425.1*	NS
b5	-0.1855***	-0.0359***	0.5337***	-238.5***	128.2***
b6	-0.2052***	NS	NS	-99.79***	NS
b7	-0.2471 ***	-0.0360***	-0.5383***	-224.5***	252.4***
R^2	0.601	0.608	0.567	0.882	0.889
P	***	***	***	***	***

*, **, *** Significant at the 5, 1 and 0.1% levels, respectively.
^a: Regression over the interval 5 to 320 weed seedlings m^-2 (n=279).
n=288.

The coefficients for selected crop canopy parameters and weed biomass are listed in Table 5. For crop parameters, the coefficients b2 to b4 were mostly non-significant (i.e.,= 0); intuitively one would anticipate that the species' regression lines have a common intercept. The slope

coefficients, b5 to b7, substantiate the greater competitiveness of *Aa* and *Sp* with wheat relative to *Lt* and *Pp;* the effects of *Lt* (b6), with the exception of crop height, did not differ markedly from *Pp.* All multiple linear regression fits were significant (P<0.001), explaining from 57 to 88% of the total variation in individual crop parameters.

The regression coefficients for weed biomass (Table 5) showed that *Aa* had a higher biomass production at low weed seedling density than the other three species (i.e., the significant b2) while *Lt* was significantly lower than *Pp; Sp* did not differ from *Pp.* Regarding the slopes of the individual regression lines for weed biomass production vs. seedling density, *Lt* was not significantly different from *Pp; Sp* and *Aa* > *Lt* and *Pp,* while *Sp* had a significantly higher rate of biomass production than *Aa.* The multiple linear regression fit was highly significant (P<0.001) and explained 89% of the variation in weed biomass production.

The coefficients for wheat grain yield and yield components are listed in Table 6. Coefficients b2 to b4 were usually not different from zero, indicating the expected common intercept values. For seeds per spike, spikes m^-2 and grain yield, *Aa* and *Sp* (i.e., b5 and b7, respectively) had the most pronounced effects, approximately doubling the rate of decline (with increasing weed density) of each crop parameter in comparison to *Pp. Lt* differed significantly from *Pp* for spikes m^-2 and grain yield but had a lesser effect than *Aa* and *Sp.* Relative to *Pp, the* other three grass weeds reduced TKW at a greater rate; again the effect of *Lt* was less than *Aa* and *Sp.* Test weight also showed a significant species differential with increasing seedling density: *Lt* and *Pp* did not differ from each other, while *Aa* and *Sp* exhibited significantly higher rates of decline. All regression fits were significant (P<0.001), explaining from 69 to 87% of the variation in the selected yield components and 90% of the variation in grain yield.

TABLE 6. Coefficients for the best fit multiple regression analyses for wheat crop yield components

	Seeds per spike	Spikes per m^2	TKW (g)	Grain yield (kg ha^-1)	Test weight (kg hl^-1)
b0	30.72	351.0	30.77	3187	77.63
b1	-0.4245***	-5.290***	-0.2064***	-88.95***	-0.2349***
b2	NS	-0.1421-	NS	-155.5**	NS
b3	-1.203***	NS	NS	NS	NS
b4	NS	NS	NS	-144.3*	-1.472***
b5	-0.7337***	-5.816***	-0.1591***	-80.47***	-0.1875***
b6	NS	-3.285***	-0.0634***	34.88***	NS
b7	-0.7465***	-7.441***	-0.1853***	-82.79***	-0.0925**
R^0	0.872	0.858	0.838	0.898	0.687
P	***	***	***	***	***

*, **, *** Significant at the 5, 1 and 0.1% levels, respectively.
n = 288.

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