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The Effects of Single- and Multiple-Weed Interference on Soybean Yield in the Far-Eastern Region of Russia

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Lack of understanding the effects of single- and multiple-weed interference on soybean yield has led to inadequate weed management in Primorsky Krai, resulting in much lower average yield than neighboring regions. A 2 yr field experiment was conducted in a soybean field located in Bogatyrka (43.82°N, 131.6°E), Primorsky Krai, Russia, in 2013 and 2014 to investigate the effects of single and multiple interference caused by naturally established weeds on soybean yield and to model these effects. Aboveground dry weight was negatively affected the most by weed interference, followed by number of pods and seeds. Soybean yield under single-weed interference was best demonstrated by a rectangular hyperbolic model, showing that common ragweed and barnyardgrass were the most competitive weed species, followed by annual sowthistle, American sloughgrass, and common lambsquarters. In the case of multiple-weed interference, soybean yield loss was accurately described by a multivariate rectangular hyperbolic model, with total density equivalent as the independent variable. Parameter estimates indicated that weed-free soybean yields were similar in 2013 and 2014, i.e., estimated as 1.72 t and 1.75 t ha^{-1}, respectively, and competitiveness of each weed species was not significantly different between the two years. Economic thresholds for single-weed interference were 0.74, 0.66, 1.15, 1.23, and 1.45 plants m^{-2} for common ragweed, barnyardgrass, annual sowthistle, American sloughgrass, and common lambsquarters, respectively. The economic threshold for multiple-weed interference was 0.70 density equivalent m^{-2}. These results, including the model, thus can be applied to a decision support system for weed management in soybean cultivation under single and multiple-weed interference in Primorsky Krai and its neighboring regions of Russia.

Nomenclature: Common ragweed, *Ambrosia artemisiifolia* L.; barnyardgrass, *Echinochloa crus-galli* (L.) Beauv.; annual sowthistle, *Sonchus oleraceus* L.; common lambsquarters, *Chenopodium album* L.; American sloughgrass, *Beckmannia syzigachne* (Steud.) Fernald; soybean, *Glycine max* (L.) Merr.

Key words: Crop–weed competition, economic threshold, modeling, multiple-weed interference, Primorsky Krai.

Soybean in the Russian Federation has mainly been cultivated in the far-eastern region of Russia including Amur Oblast, Khabarovsk Krai, and Primorsky Krai since its first introduction to the region in the 1870s (Gashkova 2008). Primorsky Krai is the southeasternmost region of Russia, with an area of 165,900 km^2, located between 42°N and 48°N and 130°E and 139°E, and bordered to the north by Khabarovsk Krai of Russia and to the west by the Heilongjiang province of China and North Korea. Although Primorsky Krai is located at a lower latitude, its soybean yield is much lower than that of its neighboring regions, including Heilongjiang province, a major soybean-producing province in China. The average soybean yield in Primorsky Krai was as low as 1.09 t ha^{-1} in 2011, much lower than the average soybean yield of 1.48 t ha^{-1} in Russia (Department of Agriculture and Food of the Primorsky Territory 2012; Food and Agriculture Organization of the United Nations 2011) and 1.69 t ha^{-1} in Heilongjiang province in China (Informa Economics 2013). The main reason for such a low soybean yield is severe weed problems and inadequate weed management. However, little or no attention has been given to establishing modern weed management practices using a decision support system based on modeled effects of single- and multiple-weed interference on soybean yield in this region.

Modeling of crop–weed competition has provided a tool to predict how crop yield is influenced by weed interference under field conditions. Under commercial-scale production, crop yield loss often occurs as a result of multiple weed species interference.

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The rectangular hyperbolic model (Cousens 1985) has most commonly been used to estimate crop yield as a function of weed density for individual weed species. Many studies expanded this approach to include the multivariate forms of the rectangular hyperbolic model that can predict crop yield resulting from multiple-weed interference by using the density equivalent of individual weed species (Berti and Zanin 1994; Kim et al. 2006a; Lindquist et al. 1998). Recent studies reported that the multivariate rectangular hyperbolic model has been useful in describing crop yield loss affected by multiple-weed interference (Oveisi et al. 2013; Yousefi et al. 2012). The multivariate rectangular hyperbolic model would be useful to evaluate the threshold level of multiple-weed interference that causes economic crop yield loss and thus to support decision making for weed control under practical field conditions.

As soybean is vulnerable to weed competition, earlier weed control is essential in its cultivation. Weeds cause severe yield loss of soybean by reducing yield components during early growth stages. The number of pods has been found to be more reduced than other yield components (Burnside and Colville 1964; Eaton et al. 1976; Knake and Slife 1962). Many efforts have been made to apply empirical models to predict the competitive effects of weeds on soybean yield. Previous studies indicated that the rectangular hyperbolic model (Cousens 1985) accurately predicted soybean yield in the presence of individual weed species such as shattercane [*Sorghum bicolor* (L.) Moench ssp. *arundinaceum* (Desv.) de Wet & Harlan] (Fellows and Roeth 1992), pigweed (*Amaranthus* spp.) (Bensch et al. 2003), common lambsquarters (Weaver 2001), and common ragweed (Cowbrough et al. 2003). Berti and Zanin (1994), Swinton et al. (1994), and Lindquist et al. (1998) developed modified versions of the rectangular hyperbolic model to predict soybean yield loss as a function of the combined density of multiple weed species. In the studies conducted by Berti and Zanin (1994) and Lindquist et al. (1998), parameters for the multivariate form of the rectangular hyperbolic model were determined based on weed competition parameters estimated for individual weed species. However, in the study conducted by Swinton et al. (1994), parameters were determined by direct regression of the soybean yields under multiple-weed interference to the multivariate rectangular hyperbolic model. There were too many parameters in the model to test experimentally, but the model accurately predicted soybean yield in response to multiple-weed interference. For example, in a particular soybean field with more than four species of weeds, the Swinton et al. (1994) approach may predict parameter estimates with higher variability, depending on weed composition and size.

Common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass are dominant in soybean fields in Primorsky Krai (Song et al. 2013) but have not been investigated for their competitive effects on soybean yield in this region. A prerequisite to support decision making for weed management and to establish effective weed management in this region is the evaluation of the competitive effects of the major weed species in a single stand (single-weed interference) or in a mixture (multiple-weed interference) on soybean yield and yield components. Therefore, this study was conducted to investigate the effects of single- and multiple-weed interference on soybean yield and to model these effects.

Materials and Methods

Field Experiments. Field experiments were conducted in 2013 and 2014 to evaluate the competitive effects of single- and multiple-weed interference on soybean yield in Bogatyrka, Russia (43.82°N, 131.6°E). Respective mean daily temperature and total rainfall during the growing season (May to October) were 16.7 C and 557.1 mm in 2013 and 15.3 C and 408.5 mm in 2014, respectively. The soil had a silty-loam texture with a CEC of 22.62 cmol kg^{-1}, organic matter content of 29.59 g kg^{-1}, total nitrogen concentration of 1.58 g kg^{-1}, inorganic NH_4^+-N concentration of 0.85 mg kg^{-1}, inorganic NO_3^--N concentration of 14.01 mg kg^{-1}, available phosphorus concentration of 18.19 mg kg^{-1}, and a pH of 6.61. An N-P-K basal fertilizer was applied at a rate of 12-31-31 kg ha^{-1} on May 27, 2013, and May 22, 2014.

Soybean ('Heinong 48') was drilled at a seeding rate of 80 kg ha^{-1} with a row width of 70 cm on May 27, 2013, and May 22, 2014. After soybean was seeded, weed species were naturally established within rows by letting weed species emerge from natural populations. Weed seedlings that were grown in premarked plots in the field were thinned to a target plant density for individual weed species and for their different plant density combinations up to the V6 stage of soybean. The weed species tested were common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass. Other weed species were removed by hand weeding. With respect to competition between soybean and single weed species, the maximum plant densities and the number of premarked plots for various plant densities of the individual weed species were as follows: common ragweed, 28 and 87 plants m^{-2} in 15 and 17 plots in 2013 and 2014, respectively; annual sowthistle, 47 and 30 plants m^{-2} in 15 and 13 plots; common lambsquarters, 137 and 80 plants m^{-2} in 16 and 13 plots; barnyardgrass, 83 and 126 plants m^{-2} in 15 and 17 plots; and American sloughgrass, 67 and 75 plants m^{-2} in 14 and 16 plots. With respect to competition between soybean and multiple weed species, the maximum total plant densities and the number of premarked plots for various plant densities of the five weed species were 145 and 120 plants m^{-2} in 96 and 84 plots in 2013 and 2014, respectively. Six weed-free plots were included for each experiment in each year. The ratio of each weed species varied from zero to one within different plant density combination plots as the five weed species naturally established within rows. The plots were laid out in a completely randomized design with a single replicate. The plot size was 4.2 by 2 m, including a buffer area. The sampling area for harvest was 2.1 m by 1 m, in which three soybean rows were included. Soybean was harvested by hand at maturity in October of each year. The soybean yield components were assessed by measuring the number of pods, number of seeds, hundred-seed weight, and dry weight of all the plants in each sampling plot. The soybean seed weight and moisture content were also measured, and the seed yield was adjusted to 14% moisture content.

Prediction Model. A rectangular hyperbolic model (Cousens 1985) was used to predict soybean yield under single-weed interference.

$$Y = \frac{Y_0}{1 + \beta x} \qquad [1]$$

where Y_0 is weed-free soybean yield and β is the competitiveness of the weed species ($1/\beta$ is the density that corresponds to 50% soybean yield loss). A multivariate rectangular hyperbolic model was selected to describe soybean yield loss caused by multiple-weed interference. For example, if two weed species were present in a soybean field, the equation for a rectangular hyperbola was rewritten to describe the relationship between soybean yield (Y) and the initial weed densities of the two weed species, denoted as 1 and 2 as follows:

$$Y = \frac{Y_0}{1 + \beta_1 X_1 + \beta_2 X_2 + \lambda X_1 X_2} \qquad [2]$$

where Y_0 is the weed-free soybean yield, β_1 and β_2 represent the competitiveness of the two weed species, λ is the interaction effect of the two weed species, and X_1 and X_2 are the initial weed densities of the two weed species. The interaction parameter λ can be omitted to make the model simpler (Kim et al. 2006a). Then, Equation 2 can be rewritten as follows:

$$Y = \frac{Y_0}{1 + \beta_1 X_1 + \beta_2 X_2} \qquad [3]$$

This model (Equation 3) can be rewritten (Equation 4) to compare relative weed competitiveness $\frac{\beta_2}{\beta_1}$ and to convert the original weed density into a relative density based on the relative competitiveness of each species, i.e., the so-called density equivalent, which is the density that results in soybean yield loss equivalent to that caused by a reference weed species 1. In this study, the reference weed species is common ragweed.

$$Y = \frac{Y_0}{1 + \beta_1 \left(X_1 + \frac{\beta_2}{\beta_1} X_2 \right)} \qquad [4]$$

In Equation 4, $X_1 + \frac{\beta_2}{\beta_1} X_2$ is the total density equivalent. The total density equivalent is the sum of the relative densities of the weeds that are calculated by multiplying the actual density of each weed with its density equivalent, i.e., the relative competitiveness of a weed to a reference weed species (Berti and Zanin 1994). If the weed community consists of n weed species, the total density equivalent is $X_1 + \frac{\beta_2}{\beta_1} X_2 + \frac{\beta_3}{\beta_1} X_3 + \ldots + \frac{\beta_n}{\beta_1} X_n$, so that soybean yield can be predicted by using Equation 5, which is a generalization of Equation 4.

$$Y = \frac{Y_0}{1 + \beta_1 \left(X_1 + \sum_{i=1} \frac{\beta_i}{\beta_1} X_i \right)} \qquad [5]$$

where Y_0 is weed-free soybean yield (%) and β_i is the competitiveness of the i^{th} weed species if β_1 is a reference weed species.

Statistical Analyses. Correlation analyses were conducted among yield components, soybean yield, and weed density to evaluate the negative effects of weed density on soybean yield and yield

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components. Nonlinear regression analyses were then conducted using the SAS PROC NLIN procedure to fit the rectangular hyperbolic model (Equation 1) and multivariate rectangular hyperbolic model (Equation 5) to the yield data corresponding to the weed density of single- and multiple-weed interference, respectively. The performance of the models was evaluated by the pseudo-R^2 of the models and the root mean square error (RMSE) of the prediction. Parameter estimates were compared between years using dummy variables (Chism et al. 1992). Significant difference ($\alpha = 0.05$) between values is determined based on whether or not the confidence intervals of the dummy variables contain zero. All statistical analyses were conducted using SAS v. 9.3 (SAS 2011).

Results and Discussion

Competitive Effects of Single-Weed Interference on Soybean Yield. Correlation and nonlinear regression analyses revealed relationships between plant density and soybean yield components in 2013 and 2014 (Figure 1). Aboveground dry weight, number of pods, and number of seeds were negatively affected by weed density regardless of species. Plant densities causing a 50% reduction in the aboveground dry weight of soybean were estimated to be 14, 20, 28, 18, and 48 plants m^{-2} in 2013 and 12, 18, 24, 17, and 23 plants m^{-2} in 2014 for common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass, respectively (Figure S1). For effect on number of pods, these values were 19, 20, 20, 17, and 36 plants m^{-2} in 2013 and 21, 22, 40, 18, and 24 plants m^{-2} in 2014 for common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass, respectively (Figure S2). The plant densities that corresponded to a 50% reduction in the number of seeds were 58, 294, 141, 323, and 233 plants m^{-2} in 2013 and 98, 87, 123, 169, and 400 plants m^{-2} in 2014 for common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass, respectively (Figure S3). The hundred-seed weight was not always correlated with density for all weed species (Figure S4). Therefore, our results indicate that aboveground dry weight and number of pods were the most vulnerable to weed density, followed by number of seeds and hundred-seed weight. Among individual components, aboveground dry weight and number of pods were the most important determinants of soybean yield. Previous studies also reported that aboveground dry weight and number of pods in soybean were the most negatively affected by weed interference during early growth (Eaton et al. 1973, 1976; Fellows and Roeth 1992), suggesting that aboveground dry weight and number of pods are determined earlier, when weed competitive effects are high, in contrast to other yield components.

Soybean yield was regressed on single-species weed density using the rectangular hyperbolic model (Figure 2 and Table 1). The Y_0 and β parameter values did not differ between years within weed species (Table S1), so the 2 yr data for each weed species were pooled, and the model was regressed on the pooled data (Figure 2 and Table 1). For the pooled data, the weed-free soybean yield was 1.73 t ha^{-1}, and the weed competitiveness values were 0.1335, 0.0828, 0.0642, 0.1505, and 0.0760 for common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass, respectively. Barnyardgrass was the most competitive weed species, followed by common ragweed, annual sowthistle, American sloughgrass, and common lambsquarters. Barnyardgrass, common ragweed, and common lambsquarters have been previously reported to cause severe yield loss in various crops, including soybean (Bosnic and Swanton 1997; Coble et al. 1981; Chikoye et al. 1995; Clewis et al. 2001; Lindquist and Kropff 1996; Vail and Oliver 1993; Weaver 2001). Barnyardgrass and common ragweed have higher competitiveness than crops, as they intercept most of the photosynthetically active radiation due to their high canopy heights (Coble et al. 1981; Lindquist and Kropff 1996). Common lambsquarters has shown variable competitiveness with crops depending on its relative emergence time (Beckett et al. 1988; Sibuga and Bandeen 1980; Weaver 2001). In our study, the low competitiveness of common lambsquarters may be attributed to delayed emergence from natural populations. American sloughgrass and annual sowthistle interference in soybean has not been reported to our knowledge.

Our study was conducted under natural field conditions in which weed species were tested using a relatively high number of plant densities with a single replicate. The number of weed densities was up to 17, almost equivalent to replicated crop–weed competition studies, which usually have four to five target densities with three replicates. Our experiment was repeated over 2 yr to assess year-to-year variation and to validate the model and parameter estimates. Our results demonstrated that the

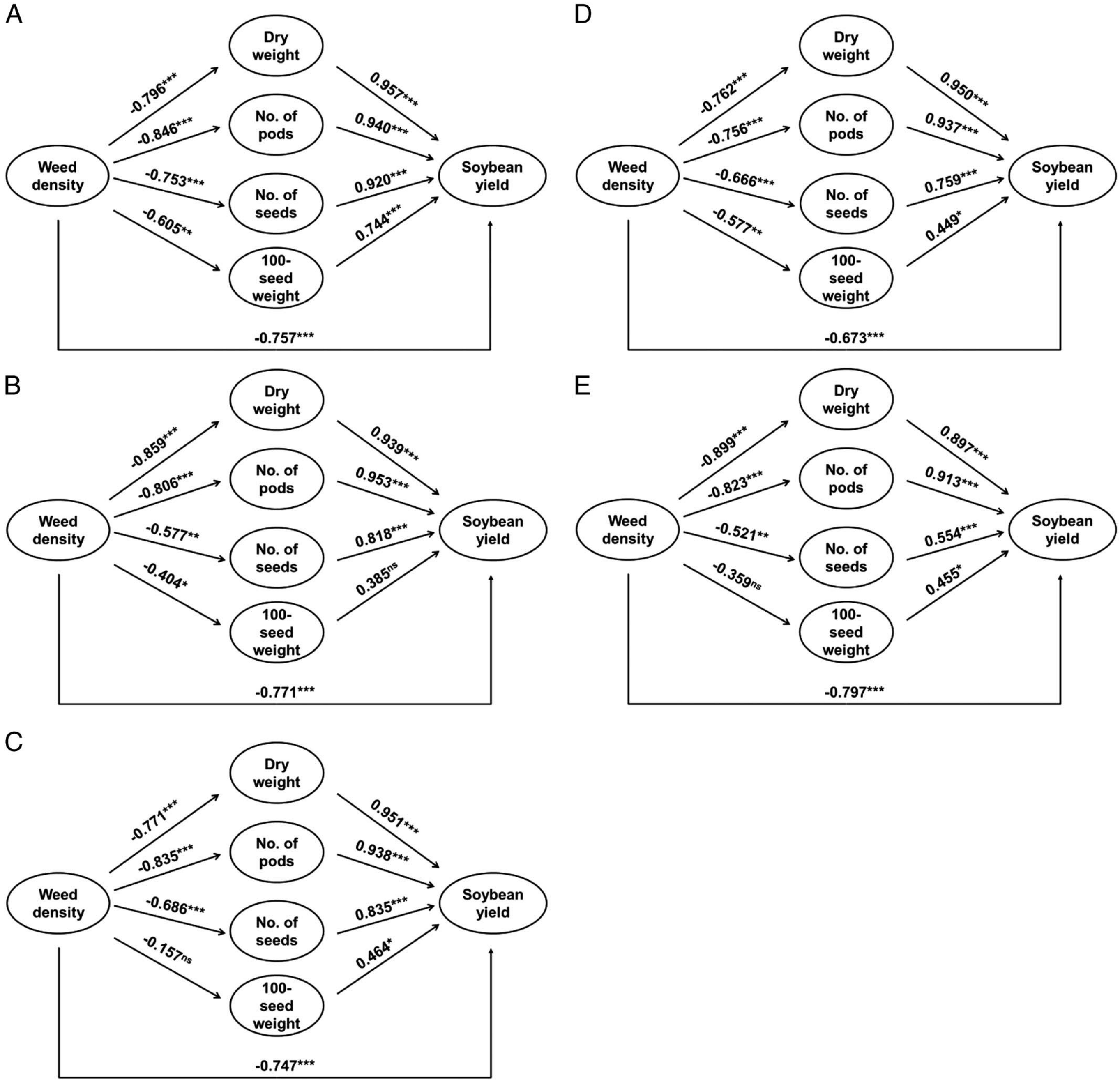

Figure 1. Schematic representations of the correlations among the plant densities of five weed species, common ragweed (A), annual sowthistle (B), common lambsquarters (C), barnyardgrass (D), and American sloughgrass (E); soybean yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight); and soybean yield over 2 yr. Significance is indicated as follows: $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

soybean yield corresponding to the densities of single weed species was accurately described by the rectangular hyperbolic model. Therefore, parameter estimates can be used for estimating weed competitive effects on soybean yield under natural field conditions.

Competitive Effects of Multiple-Weed Interference on Soybean Yield. The competitiveness of individual weed species was converted into a density equivalent using common ragweed as the reference species (Table 2). Based on pooled data, the density equivalents of common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass were 1.00, 0.62, 0.48, 1.13, and 0.57, respectively. Various plant density combinations of the five weed species were converted into a total density equivalent by multiplying the actual density of each weed with its density equivalent. Correlation analysis indicated that the

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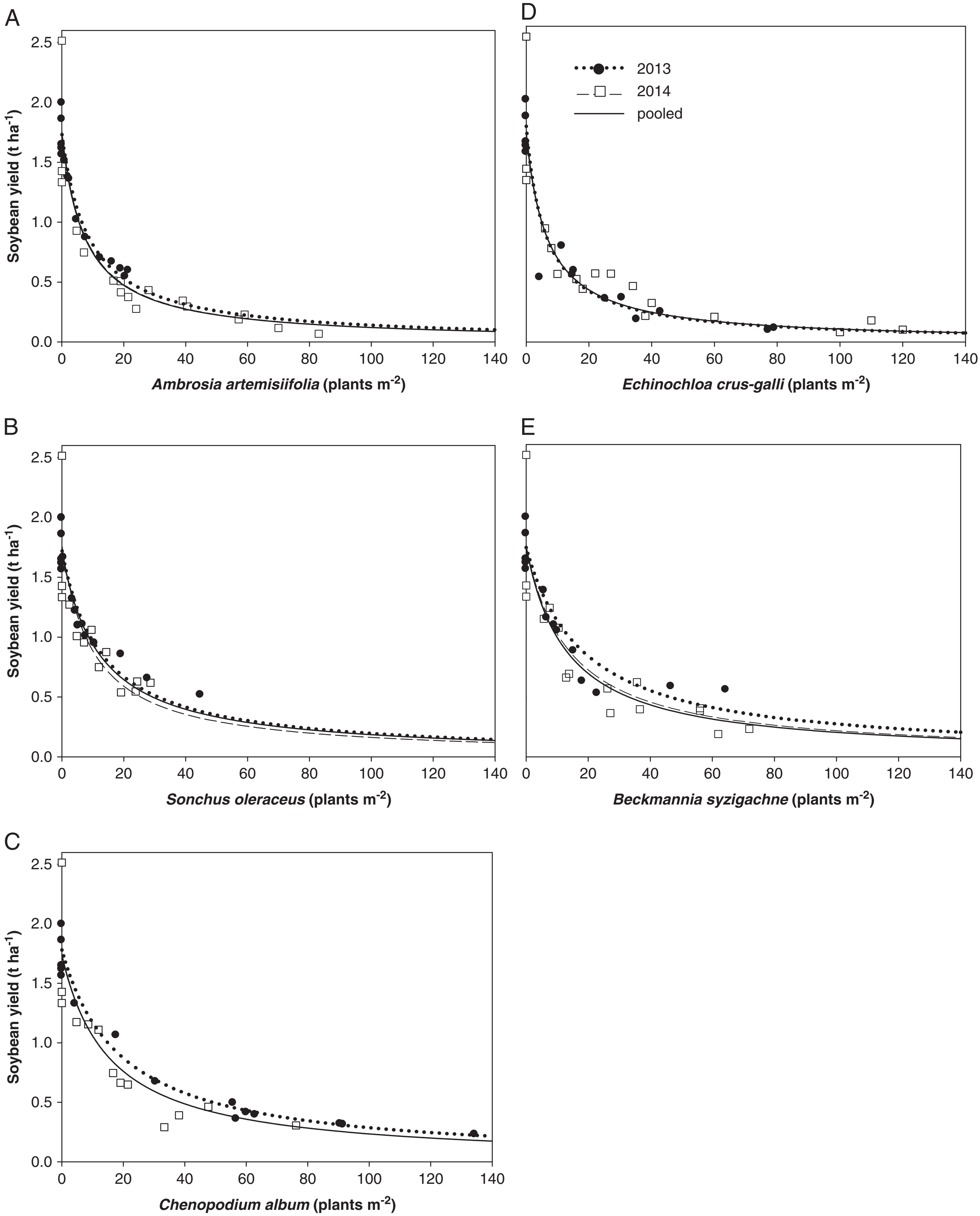

Figure 2. Soybean yield as a function of weed density of common ragweed (A), annual sowthistle (B), common lambsquarters (C), barnyardgrass (D), and American sloughgrass (E) in 2013 (dotted line) and 2014 (dashed line) and in the pooled 2 yr (solid line) data. The lines are fitted values calculated using the rectangular hyperbolic model (Equation 1) and parameter estimates (Table 1).

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Table 1. Parameter estimates for the rectangular hyperbolic model for the regression of soybean yield as a result of single-weed interference caused by common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass in 2013 and 2014 and in the pooled 2 yr data.

	Parameter[a]														
	Y_0			β			df			RMSE			Pseudo-R^2		
Weed species	2013	2014	Pooled	2013	2014	Pooled	2013	2014	Pooled	2013	2014	Pooled	2013	2014	Pooled
Common ragweed	1.719 (0.047)	1.747 (0.141)	1.737 (0.065)	0.1116 (0.0136)	0.1571 (0.0415)	0.1335 (0.0192)	13	15	30	0.115	0.247	0.195	0.95	0.85	0.91
Annual sowthistle	1.710 (0.053)	1.706 (0.163)	1.712 (0.071)	0.0739 (0.0109)	0.0897 (0.0290)	0.0828 (0.0138)	13	11	26	0.131	0.302	0.219	0.92	0.71	0.81
Common lambsquarters	1.731 (0.049)	1.757 (0.166)	1.736 (0.074)	0.0497 (0.0059)	0.0773 (0.0240)	0.0642 (0.0105)	14	11	27	0.112	0.297	0.215	0.97	0.79	0.89
Barnyardgrass	1.718 (0.081)	1.744 (0.147)	1.726 (0.077)	0.1770 (0.0387)	0.1371 (0.0364)	0.1505 (0.0256)	13	15	30	0.181	0.256	0.220	0.94	0.84	0.90
American sloughgrass	1.738 (0.068)	1.764 (0.154)	1.751 (0.089)	0.0653 (0.0105)	0.0855 (0.0229)	0.0760 (0.0118)	12	14	28	0.155	0.273	0.222	0.91	0.81	0.86

[a] The numbers in parentheses are the standard errors.

Table 2. Density equivalent of individual weed species using common ragweed as the reference weed species in 2013 and 2014 and in the pooled 2 yr data.

	Density equivalent		
Weed species	2013	2014	Pooled
Common ragweed	1.00	1.00	1.00
Annual sowthistle	0.66	0.57	0.62
Common lambsquarters	0.45	0.49	0.48
Barnyardgrass	1.59	0.87	1.13
American sloughgrass	0.59	0.54	0.57

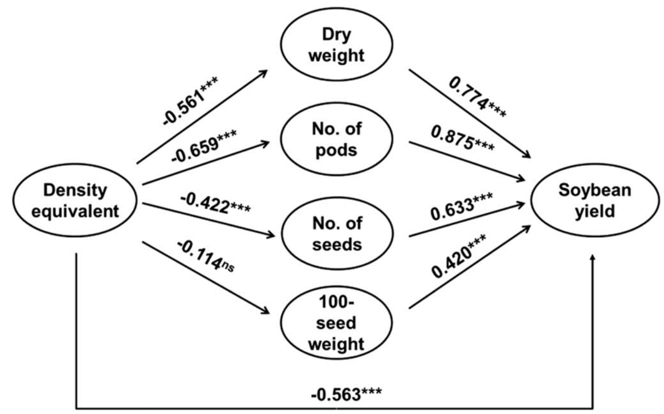

Figure 3. Schematic representations of the correlations among the total density equivalents of the five weed species, common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass; soybean yield components (no. of pods, no. of seeds, 100-seed weight, and dry weight); and soybean yield over 2 yr. Significance is indicated as follows: ***$P < 0.001$.

total density equivalent was negatively correlated with aboveground dry weight, number of pods, and number of seeds, regardless of year (Figure 3), resulting in negative effects on soybean yield.

The multivariate rectangular hyperbolic model (Equation 5) was then used to model the competitive effects of multiple-weed interference on soybean yield. Soybean yield was regressed on total density equivalent of the five weed species using the multivariate rectangular hyperbola model (Equation 5, Table 2). Pairwise comparison of parameter estimates showed that the two parameter values did not differ between years (Table S1), so the 2 yr data were pooled (Figure 4). For the pooled data, the weed-free soybean yield and the multiple-weed competitiveness values were 1.72 t ha^{-1} and 0.1423, respectively (Table 3). The model accurately described the soybean yield influenced by the multiple-weed interference (Figure 4). Previous studies also reported that the multivariate

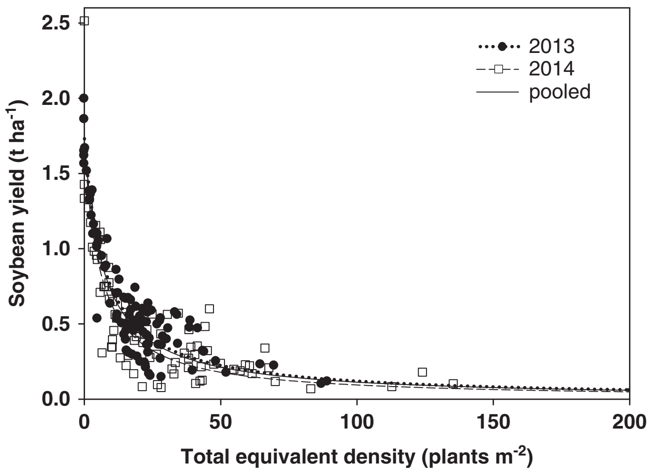

Figure 4. Soybean yield as a function of the total density equivalent (Table 2) in 2013 (dotted line) and 2014 (dashed line) and in the pooled 2 yr (solid line) data. The lines are fitted values calculated using the multivariate rectangular hyperbolic model (Equation 5) and parameter estimates (Table 3).

rectangular hyperbolic model provided a good description of the grain yield of crops in the presence of multiple weed species, even though the model was tested in a single-replicate experiment (Kim et al. 2006a; Oveisi et al. 2013) or without replications (Berti and Sattin 1996). Therefore, the multivariate rectangular hyperbolic model tested in our study can be used for predicting soybean yield under natural field conditions.

Table 3. Parameter estimates for the multivariate rectangular hyperbolic model for the regression of soybean yield affected by multiple-weed interference expressed as the density equivalent in 2013 and 2014 and in the pooled 2 yr data.

Year	Parameter[a] Y_0	β	df	RMSE	Pseudo-R^2
2013	1.7575 (0.0552)	0.1307 (0.0092)	94	0.1380	0.887
2014	1.6790 (0.1000)	0.1603 (0.0205)	82	0.1991	0.750
Pooled	1.7229 (0.0547)	0.1423 (0.0099)	178	0.1739	0.818

[a] The numbers in parentheses are the standard errors.

Economic Thresholds and Decision Support. The model tested here can be used to determine the economic thresholds (ETs) for single- and multiple-weed interference in soybean production in Primorsky Krai, Russia. According to a number of studies (e.g., Cousens 1987; Marra and Carlson 1983; Zanin et al. 1993), the ETs of weed species can be predicted by comparing the cost of controlling weed species with the benefit gained by herbicide application. In this region, dimethenamid-p followed by bentazon + acifluorfen is commonly used for respective PRE and POST weed control. In 2012, the soybean price and weed control costs were US\$470 t^{-1} and US\$62.6 ha^{-1}, respectively. Using these values, the proportion of yield loss caused by unit weed density obtained in our study, and assuming a 90% herbicide efficacy, the calculated ETs are 0.74, 1.15, 1.45, 0.66, and 1.23 plants m^{-2} for common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, and American sloughgrass in the pooled 2 yr data, respectively (Table 4). In addition, the ETs of multiple weed species would be 0.70 density equivalent m^{-2} in the pooled 2 yr data (Table 4). Barnyardgrass and common ragweed were the most competitive individual weed species and most predominant in our soybean fields, and their ETs were much lower than those of the other weeds. PRE herbicides such as alachlor, acetochlor, flumioxazin, metribuzin, and

Table 4. The economic threshold (ET) of single weed species, including common ragweed, annual sowthistle, common lambsquarters, barnyardgrass, American sloughgrass, and multiple weed species in the pooled 2 yr data.

Weed species	Parameter estimates and ETs C_h (\$ ha^{-1})	C_a (\$ ha^{-1})	Y_0 (t ha^{-1})	P (\$ t^{-1})	L	H	ET[a]
Common ragweed[b]	56.5	6.1	1.7	470	0.118	0.90	0.74
Annual sowthistle	56.5	6.1	1.7	470	0.076	0.90	1.15
Common lambsquarters	56.5	6.1	1.7	470	0.060	0.90	1.45
Barnyardgrass	56.5	6.1	1.7	470	0.131	0.90	0.66
American sloughgrass	56.5	6.1	1.7	470	0.071	0.90	1.23
Multiple weed species	56.5	6.1	1.7	470	0.125	0.90	0.70

[a] $ET = \frac{C_h + C_a}{Y_0 PLH}$, where C_h is herbicide cost (US\$ ha^{-1}); C_a is application cost (US\$ ha^{-1}); Y_0 is weed-free crop yield (t ha^{-1}); P is value per unit crop (US\$ t^{-1}); L is a proportional loss per unit weed density; and H is herbicide efficacy (% weed control/100).

[b] ET of a single weed species is expressed as number of weed plants m^{-2}, while the ET of multiple weed species is expressed as the total density equivalent m^{-2}.

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prometryn can effectively control common ragweed in addition to a wide spectrum of grass and broadleaf weeds when applied at planting (Han et al. 2002; Kapusta 1979). After soybean establishment, POST herbicides such as bentazon, imazethapyr, acifluorfen, haloxyfop, and clethodim can be selectively used for weed control (Hager and Renner 1994; Han et al. 2002). In conclusion, the weed-free soybean yield, weed competitiveness, and ETs determined in this study can support decision making for weed management based on herbicide use in soybean production in Primorsky Krai and neighboring regions such as Amur Oblast and Khabarovsk Krai in Russia and Heilongjiang province in China.

Model Validation and Further Studies. Our study showed that the parameter estimates in weed-free soybean yield and weed competitiveness were stable across years at the Bogatyrka field site (Table S1), although the observed data in 2014 exhibited slightly higher variation than those in 2013. Previous studies also reported that estimated weed-free yield (Harrison et al. 1985) or estimated weed competitiveness in soybean were not different among years at a given site (Bensch et al. 2003; Dieleman et al. 1995). However, crop–weed competition in various crops can differ among years and locations depending on the environmental conditions and cultural practices. Variations in interference relationships have been mainly attributed to low soil moisture throughout the growing season (Baysinger and Sims 1991; Coble et al. 1981; Harrison 1990; Lindquist et al. 1996; Webster et al. 1994) and partially due to the different soil types (Peterson and Nalewaja 1992), disease pressure (Lindquist 2001), relative time of weed emergence (Lindquist et al. 1999; Moon et al. 2010), row spacing (Hock et al. 2006a, 2006b), and rate of nitrogen fertilization (Kim et al., 2006b). While the model used in our study accurately described the competitive effects of single- and multiple-weed interference on soybean yield under the same field conditions, further studies should be conducted to validate the parameters of the multivariate rectangular hyperbolic model for other genetic (e.g., cultivar) and cultural practices (e.g., row spacing, nitrogen fertilizer). Although the model and parameter estimates need to be further validated for a broad range of years and locations, this type of research can support decision making more effectively with respect to herbicide use in soybean cultivation across Primorsky Krai and neighboring regions.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1614/WS-D-16-00091.1

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