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Common Ragweed (*Ambrosia artemisiifolia* L.) Interference with Soybean in Nebraska

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ABSTRACT

Common ragweed is a competitive weed in soybean fields in north central United States and eastern Canada. The effect of available soil water on the competitiveness of common ragweed in soybean hasn't been determined. A field study was conducted in 2015 and 2016 in Nebraska to assess common ragweed interference in soybean as affected by available soil water and common ragweed density. The experiment was arranged in a split-plot design with irrigation level as main plots and common ragweed density as subplots. Periodic crop and weed leaf area index (LAI) and aboveground biomass were sampled and soybean yield was harvested. A model set was constructed using the rectangular hyperbolic and leaf area ratio models and the best model for predicting yield loss among years was identified using the information-theoretic criterion. No effect of irrigation level on soybean yield was detected due to near adequate rainfall during the study. Common ragweed densities of 2, 6, and 12 m^{-1} row resulted in soybean yield losses of 76, 91, and 95% in 2015 and 40, 66, and 80% in 2016, respectively. The leaf area ratio model using relative leaf area at the R6 growth stage of soybean best fit the data. The leaf area ratio model includes both soybean and common ragweed leaf area and, therefore, is putatively more effective at accounting for variation in competition for light than density among years. Results of this study suggest that soybean-common ragweed interference resulted in substantial soybean yield loss when competing for light.

Core Ideas

- Interference of common ragweed in soybean was driven by competition for light.
- The leaf area ratio model at R6 growth stage was a robust predictor of yield loss.
- Twelve common ragweed m^{-1} row length resulted in 80-95% soybean yield loss.

Common ragweed (*Ambrosia artemisiifolia* L.) is an herbaceous, annual weed, native to North America (Coble et al., 1981). Common ragweed seeds can remain viable in the soil for as long as 39 yr, allowing it to survive in many environments (Bassett and Crompton 1975). Cold stratification is required for the seeds to germinate (Bazzaz 1970). Germination occurs near the soil surface in early spring (Bazzaz 1970). Common ragweed plants have a fibrous root system and can grow over 2 m in height (Bassett and Crompton 1975; Clewis et al., 2001). When grown in a non-competitive environment, a small (95 g fresh weight) and a large (2400 g fresh weight) common ragweed plant produced 3135 to 62,000 seeds, respectively (Dickerson and Sweet 1971). Common ragweed is a competitive weed in soybean [*Glycine max* (L.) Merr.] (Coble et al., 1981). Common ragweed plants at densities of 4 plants 10 m^{-1} of row reduced soybean yield up to 8% (Coble et al., 1981). Weaver (2001) and Shurtleff and Coble (1985) reported two common ragweed m^{-1} row caused 11 and 12% soybean yield loss, respectively.

Two of the major resources that crop and weeds compete for are light and water (Massinga et al., 2003). Light interception in competitive environments is determined by the leaf area index (LAI), vertical leaf area distribution, plant height, and light absorption characteristics of the species (Kropff 1993). Light interception affects biomass accumulation and transpiration (Deen et al., 2003). Plant growth in response to an increase in light availability only occurs when the demand for carbon is greater than the supply in a plant (Craine and Dybzinski 2013). Maximizing photosynthetic rates and limiting the photosynthetic rate and subsequent growth of a competing species are the direct and indirect benefits of producing leaves above those of a competitor (Falster and Westoby 2003). The advantages of increased height eventually are outweighed by the increased risk of cavitation or lodging (Falster and Westoby 2003). Plant competition for light has led to species maintaining greater than optimal leaf area required to maximize carbon gain in the absence of competition (Anten 2005) and provides a greater advantage than disadvantage (Craine and Dybzinski 2013).

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Abbreviations: ET, evapotranspiration; Kc, crop coefficient; LAI, leaf area index; ME, modeling efficiency; RLA, relative leaf area

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Under drought stress, both crop yield and weed growth are reduced (Radosevich et al., 1997). Irrigation is a cultural practice that can directly affect interspecific competition between weeds and soybean, ultimately affecting soybean seed yield (Norsworthy and Oliver 2002). Optimal irrigation early in the growing season may maximize crop growth, allowing earlier canopy closure and thus, reducing interspecific competition later in the growing season (Yelverton and Coble 1991). Redroot pigweed (*Amaranthus retroflexus* L.), robust white foxtail (*Setaria viridis* var. robusta-alba Schreiber), and robust purple foxtail (*Setaria viridis* var. robusta-purpurea Schreiber) interference with soybean was more severe during a year with low water availability (Orwick and Schreiber 1979). Soybean yield loss due to yellow foxtail (*Setaria glauca* L.) was less when growing season soil water was sufficient (Staniforth and Weber 1956). Weber and Staniforth (1957) reported Pennsylvania smartweed (*Polygonum pensylvanicum* L.) and giant foxtail (*Setaria faberi* L.) reduced soybean yield more when moisture was limiting. Pitted morningglory (*Ipomoea lacunosa* L.) was more competitive with soybean in a dry year, reducing soybean yield 17% over the wet year (Howe and Oliver 1987). Entireleaf morningglory (*Ipomoea hederacea* var. integriuscula Gray) at a density of three plants m^{-2} reduced soybean yield 21% under dryland and 12% under irrigated conditions (Mosier and Oliver 1995). Mortensen and Coble (1989) reported common cocklebur (*Xanthium strumarium* L.) caused less soybean yield loss in well watered versus drought-stressed conditions.

Scientific literature is not available on the effect of density of common ragweed and available soil water on soybean yield. The hypothesis of this study was that limited available soil water would benefit the competitive ability of common ragweed over soybean. The objective of this study was to identify the best statistical model of the competitive interaction between soybean and common ragweed as influenced by increasing weed density and available soil water. Specifically, soybean yield loss was fit to common ragweed density, aboveground biomass, LAI, and leaf area ratio to (i) determine the effect of available soil water and common ragweed density on soybean yield and (ii) determine the most robust method for describing soybean yield loss across variable available soil water levels and year to year variation.

MATERIALS AND METHODS

A field experiment was conducted over a 2-yr period (2015, 2016) at the University of Nebraska-Lincoln's Agriculture Research and Development Center (ARDC) near Mead, Nebraska (41.16, −96.42). The soil classification at the experimental site was a Filbert silt loam (fine, smectitic, mesic Vertic Argialbolls; 25.6% clay, 63.6% silt, 10.8% sand). The field contained 2.7% soil organic carbon and had a pH of 6.8. The experiment was arranged in a split-plot design with four replications. The main plot treatments were non randomized irrigation levels established to achieve full, half, or zero replacement of simulated evapotranspiration (ET) using the recommendations of SoyWater (Specht et al., 2010). SoyWater utilizes a reference ET multiplied by a soybean crop coefficient (Kc; Specht et al., 2010). Cumulative daily soybean ET is used to estimate how much water is used by the crop and when irrigation should be scheduled (Specht et al., 2010). Irrigation levels were established as distance from a solid set sprinkler irrigation system, as the distribution of irrigation intensity has been shown to decline with distance (Specht et al., 1986, 2001). Full (100%), half (50%), and zero (0%) irrigation main plots were centered 2.3, 9.9, and 19 m from the solid set irrigation system, respectively. Within each irrigation main plot, there were five randomized subplots of common ragweed density, including 0 (weed-free control), 2, 6, and 12 common ragweed plants m^{-1} row with soybean crop, and two common ragweed plants m^{-1} row without crop. Subplots were 3 m wide (four soybean rows spaced 0.76 m apart) × 9 m long.

Experimental Procedures

The experimental site was disked in early spring to prepare a uniform seedbed. Common ragweed seeds (Roundstone Native Seed LLC, Upton, KY) were broadcast by hand on 30 Apr. 2015 and 22 Apr. 2016 to ensure enough plants to establish target densities. Approximately 50% common ragweed emergence was observed on 17 May 2015 and 27 May 2016. High rainfall (11 cm) caused some of the plots to become flooded for several days from 9 to 12 May 2016 resulting in anoxic soil conditions that killed germinating and emerged common ragweed seedlings. Therefore, 2016 common ragweed emergence was delayed. Soybean was planted at 370,500 seeds ha^{-1} to the entire field (84 × 108 m) on 13 May 2015 (Pioneer 21T11) and 19 May 2016 (Asgrow 2636). Buffers between main plots and the perimeter border were maintained weed free by applying glyphosate (900 g a.e. ha^{-1}) and hand hoeing as required. Uniform soybean emergence in 2015 and 2016 occurred on 23 and 27 May, respectively. Common ragweed was thinned by hand to the required densities in a 15-cm band over the soybean row prior to reaching the V2 leaf stage of development. Natural weed populations were removed by hand hoeing throughout the season. Irrigation was applied on 3 Aug. 2015 (100%, 3.8 cm [±0.12]; 50%, 1.6 cm [±0.09]), 25 July 2016 (100%, 3.8 cm [±0.18]; 50%, 1.4 cm [±0.16]), and 9 Aug. 2016 (100%, 0.7 cm [± 0.05]; 50%, 0.4 cm [±0.04]).

Data Collection

Daily precipitation and minimum and maximum air temperature were acquired from a High Plains Regional Climate Center (HPRCC) station near Ithaca, NE, approximately 5.5 km from the experimental site. Destructive samples of soybean and common ragweed leaf area, and aboveground biomass were taken at the V3, R1, R4, and R6 stages of soybean growth. During the R6 destructive sample in 2015 only the 0 and 100% irrigation main plots were sampled and the only data recorded were the leaf area of common ragweed and soybean. Soybean and common ragweed plants within 1 m of row located at least 0.5 m from the plot edge were counted and clipped at the soil surface. Soybean and common ragweed leaves were removed at the point of attachment of the petiole to the stem and leaf area (m^2) was measured using a leaf area meter (LAI 3100, LI-COR, Lincoln, NE). During the V3 and R1 samplings in 2015, soybean and common ragweed leaf area was measured from the entire 1 m sample. Leaf area was measured on four random soybean and two random common ragweed plants from each 1 m sample at all other sampling events due to time and labor constraints. Number of plants taken within each destructive sample was then converted to plants m^{-2}.

Table 1. Average soybean seed yield by irrigation level and common ragweed density treatments in 2015 and 2016.

Irrigation level	Common ragweed density (m row^{-1})	2015 Yield (kg ha^{-1})	2015 SEM	2016 Yield (kg ha^{-1})	2016 SEM
0%	0	5357.5	142.4	4437.6	114.2
	2	1356.9	191.8	2944.4	150.7
	6	260.1	55.5	1548.9	226.9
	12	132.8	23.3	856.7	139.2
50%	0	5261.4	255.2	4403.1	98.4
	2	1094.0	250.7	3423.3	200.9
	6	750.5	183.3	1593.5	144.3
	12	360.8	181.1	588.3	12.8
100%	0	4910.7	199.6	4424.6	133.6
	2	1009.1	77.0	2747.6	116.8
	6	354.0	76.7	1264.0	279.5
	12	248.7	69.7	663.4	140.5

The LAI from soybean and common ragweed leaf area measurements were calculated as:

$$LAI = \frac{LA}{N_i} \times N_0 \quad [1]$$

where LA is the leaf area measured (m^2), N_i is the number of plants sampled for LA, N_0 is the number of plants m^{-2}. Aboveground biomass of soybean and common ragweed was obtained from the entire 1 m row sample after drying to constant weight at 65°C. Soybean was harvested by hand and threshed using a plot combine from 3.05 m of the center two rows on 5 Nov. 2015 and 21 Oct. 2016. Soybean grain was weighed and average grain moisture content obtained from three subsamples using a Dickey John GAC 2100 grain moisture tester (DICKEY-john, Auburn, IL). Soybean yield was adjusted to 13% moisture and converted to kg ha^{-1} (Table 1). Whole plot common ragweed density was determined from the soybean harvest area prior to harvest and converted to plants m^{-1} row.

Model Configuration

Soybean yield loss (%) was calculated as:

$$YL = 100 \times (1- P/C) \quad [2]$$

where YL is the yield loss relative to the weed-free control, P is the plot yield, and C is the mean weed-free control yield from the associated main plots. Data were tested for normality before analysis. Yield loss was modeled using two equations with multiple parameterizations in R version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria). The first was the rectangular hyperbolic yield loss model (Cousens 1985):

$$YL = (I \times N)/(1 + (I \times N)/A) \quad [3]$$

where YL is yield loss, I is the slope of the yield loss curve as density approaches zero (sometimes referred to as the damage coefficient), A is the maximum yield loss bound between 0% and 100%, and N is the independent variable. Eight permutations were constructed with differing independent variables (N), including whole plot common ragweed density (density; m^{-1} row), common ragweed LAI obtained at four sampling times (V3, R1, R4, and R6), and common ragweed biomass (BM; m^{-1} row) at three sampling times (V3, R1, and R4). The second model was the leaf area ratio model (Kropff et al., 1995):

$$YL = (q \times L_w)/(1 + (q/A - 1) \times L_w) \quad [4]$$

where YL is yield loss, q is the relative damage coefficient, A is the maximum yield loss bound between 0% and 100%, and L_w is the relative leaf area (RLA) of the weed calculated as:

$$L_w = W_{LAI}/(C_{LAI} + W_{LAI}) \quad [5]$$

where W_{LAI} is the LAI of the weed and C_{LAI} is the LAI of the crop. L_w was calculated for each of the four sampling times (V3, R1, R4, and R6) and used for four permutations of Eq. [5]. Parameter differences between irrigation levels within year were assessed for each model permutation using F-tests (Knezevic et al., 1994). If model parameters did not vary by irrigation level, the data were pooled across irrigation levels. Parameter differences between years were then assessed using F-tests. If model parameters did not vary between years, the data were pooled across years and the model fitted to the pooled data. Model permutations fitted to the same-pooled dataset were compared using the information-theoretic model criterion (AIC) (Anderson 2008). The use of the information-theoretic criteria for comparing crop-weed competition models provides empirical support for multiple well-established models while reducing risk of misinformation or poor performance (Jasieniuk et al., 2008). The corrected AIC (AICc) and model probability (AICw) were obtained for the models using the *AICcmodavg* package in R version 3.3.2 (R Foundation). The corrected AIC (AICc) was calculated as (Anderson 2008):

$$\mathrm{AICc} = -2LL + 2K(n/[n - K - 1]) \quad [6]$$

where K is the number of model parameters, LL is the maximum log likelihood, and n is the sample size. AICw was calculated as (Anderson 2008):

$$\mathrm{AICw}_i = [\exp\left(-\frac{1}{2\Delta i}\right) / \sum_{r=1}^{R} \exp\left(-\frac{1}{2\Delta r}\right)] \quad [7]$$

where Δi is the difference between the model with the lowest AIC and the i*th* model, R represents the total number of models being compared, and Δr is the difference between the

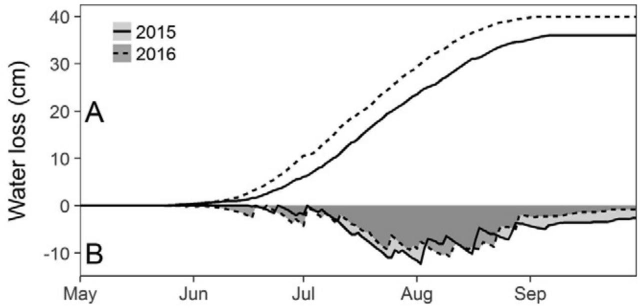

Fig. 1. A) Cumulative soybean evapotranspiration (ET; cm) and B) cumulative available soil water deficit (cm) obtained from SoyWater (http://www.hprcc3.unl.edu/soywater/) in a field experiment conducted at the University of Nebraska-Lincoln in 2015 and 2016.

model with the lowest AIC and the *rth* model. The model with the lowest AICc and the highest AICw is considered the best predictor of the results within the model set (Anderson 2008).

Model Goodness of Fit

The RMSE and modeling efficiency (ME) of the best model were calculated to evaluate goodness of fit. The RMSE was calculated as (Roman et al., 2000):

$$\mathrm{RMSE} = [1/n\sum_{\mathrm{i=1}}^{n}(Pi - Oi)^2]^{1/2} \qquad [8]$$

where Pi and Oi are the predicted and observed values respectively and n is the total number of comparisons. The lower the RMSE, the closer the model predicted values are to the observed values. The ME was calculated as (Mayer and Butler 1993):

$$\mathrm{ME} = 1 - [\sum_{\mathrm{i=1}}^{\mathrm{n}}(Oi - Pi)^2 / \sum_{\mathrm{i=1}}^{n}\left(Oi - \bar{O}i\right)^2\Big] \qquad [9]$$

where $\bar{O}i$ is the mean observed value and all other parameters are the same as Eq. [8]. The ME differs from R^2 only in not having a lower limit. The ME values closest to 1 indicate the most accurate predictions.

RESULTS

Irrigation Level

SoyWater estimated cumulative soybean ET of 36 and 40 cm in 2015 and 2016, respectively (Fig. 1). Available soil water was rarely depleted due to frequent rain events in both years of this study (Fig. 1). Model parameters did not vary between irrigation level for any model permutation in either year of this study (Table 2), so all datasets were pooled across irrigation levels within a year with only density treatments considered.

Year-to-Year Variation

Temperature and precipitation were similar throughout the two growing seasons (Fig. 2). Parameters I and q did not vary among years for the rectangular hyperbolic yield loss model fitted to R6 LAI and the leaf area ratio model fitted to R6 RLA, respectively. Therefore, the 2015 and 2016 data were pooled for those two model permutations (Table 3). Parameters I and

Table 2. Variation in yield loss model parameters across irrigation levels (100%, 50%, and 0%) for multiple destructive samples in 2015 and 2016.†

				2015			2016		
Model	Stage	Method	Parameter	F-value	P-value ‡		F-value	P-value ‡	
Rectangular hyperbola	–	Density	I	0.162	0.8509	NS	1.487	0.2369	NS
			A	0.609	0.5483	NS	0.000	0.9999	NS
	V3	LAI	I	0.824	0.4452	NS	0.161	0.8518	NS
			A	0.353	0.7045	NS	0.414	0.6635	NS
	R1	LAI	I	2.138	0.1297	NS	1.269	0.291	NS
			A	0.144	0.8663	NS	1.000	0.3759	NS
	R4	LAI	I	0.910	0.4098	NS	0.298	0.7438	NS
			A	0.114	0.8925	NS	0.301	0.7416	NS
	R6	LAI	I	0.025	0.8754	NS	0.216	0.6455	NS
			A	0.617	0.5441	NS	0.266	0.7676	NS
	V3	BM	I	0.587	0.5602	NS	0.392	0.678	NS
			A	0.633	0.5357	NS	0.728	0.4885	NS
	R1	BM	I	3.102	0.0547	NS	0.767	0.4704	NS
			A	0.095	0.9096	NS	0.000	0.9999	NS
	R4	BM	I	0.701	0.5014	NS	0.000	0.9999	NS
			A	0.000	0.9999	NS	0.000	0.9999	NS
Leaf area ratio	V3	RLA	q	0.939	0.3985	NS	0.703	0.5005	NS
			A	0.585	0.5613	NS	0.980	0.3832	NS
	R1	RLA	q	2.376	0.1045	NS	0.983	0.3821	NS
			A	0.495	0.6129	NS	0.119	0.8881	NS
	R4	RLA	q	2.213	0.1211	NS	0.400	0.6727	NS
			A	0.484	0.6195	NS	0.000	0.9999	NS
	R6	RLA	q	0.219	0.8042	NS	0.421	0.6589	NS
			A	0.990	0.3795	NS	0.537	0.5882	NS

† Density, common ragweed density at harvest; BM, common ragweed aboveground biomass; LAI, leaf area index of common ragweed; NS, nonsignificant at α = 0.05; RLA, common ragweed relative leaf area; V3, R1, R4, R6, soybean stage at destructive sampling.

‡ NS, nonsignificant; *, P < 0.05; **, P < 0.01; ***, P < 0.001.

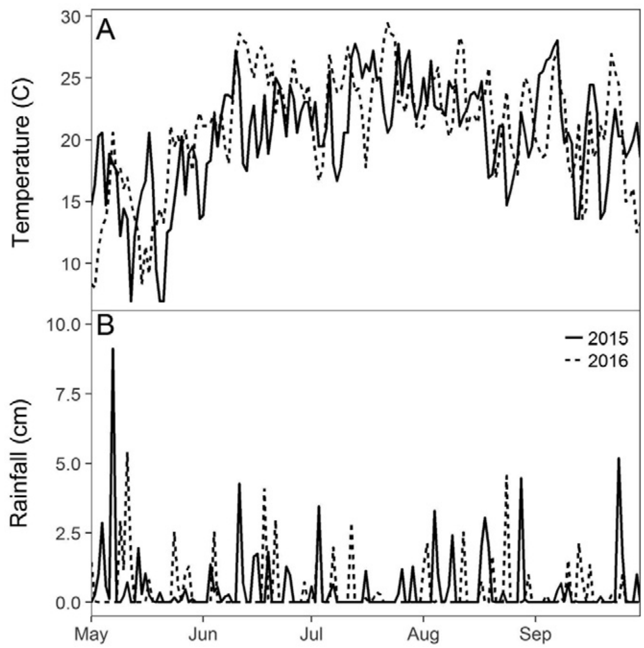

Fig. 2. A) Average daily air temperature (°C) and B) total daily precipitation (cm) obtained from the nearest High Plain Regional Climate Center in a field experiment conducted at the University of Nebraska-Lincoln in 2015 and 2016.

q did vary between years for all other model permutations, so analyses were conducted separately for 2015 and 2016 for those model permutations (Table 3). For example, the rectangular hyperbolic yield loss model (Eq. [3]) fitted to V3 aboveground biomass resulted in *I* values of 872 and 23 in 2015 and 2016, respectively (Table 4). Parameter *A* did not vary between year for any model permutation or sampling time (Table 3). All rectangular hyperbolic yield loss model (Eq. [3]) permutations predicted maximum yield loss (*A*) between 87 and 100% (Table 4). All leaf area ratio model (Eq. [4]) permutations predicted maximum yield loss between 93 and 100% (Table 4).

All models fitted separately by year provided acceptable fit of the data with ME ranging from 89 to 99 in 2015 and from 74 to 92 in 2016 (Table 4). All model permutations had greater damage coefficients (*I* or *q*) in 2015 than 2016 (Table 4). In 2015, Eq. [3] fitted to common ragweed aboveground biomass at the R4 growth stage provided the best fit to the data with the lowest AICc and 100% of the AICw (Table 4). This model fit the data well with an ME of 99 and RMSE of 22 (Table 4). Early-season destructive samples (V3 stage) in 2015 proved to be the worst predictors of soybean yield loss (Table 4). Equation [3] fitted to common ragweed density m^{-1} row was the best fit of the 2016 soybean yield loss data with the lowest AICc and carrying 100% of the model probability (Table 4). This model was well fit to the data with an ME of 92 and RMSE of 87 (Table 4). Common ragweed aboveground biomass and LAI at the V3 sampling were the worst predictors of soybean yield loss in 2016.

The pooled 2015 and 2016 soybean yield loss was tightly correlated to late destructive samples (R6) of LAI. Common ragweed RLA sampled at soybean R6 growth stage in 2015 and 2016 and used to fit Eq. [4] resulted in *q* and *A* parameter estimates of 562 and 96, respectively (Fig. 3). The goodness of fit tests resulted in an ME of 91 and RMSE of 159 (Fig. 3). Common ragweed LAI sampled at soybean R6 growth stage

Table 3. Variation in yield loss model parameters across years for multiple destructive samples in 2015 and 2016.†

Model	Stage	Method	Parameter	*F*-value	*P*-value ‡	
Rectangular hyperbola	–	Density	I	6.473	0.0127	*
			A	0.120	0.7298	NS
	V3	LAI	I	10.288	0.0019	**
			A	0.279	0.5987	NS
	R1	LAI	I	15.680	0.0001	***
			A	0.026	0.8723	NS
	R4	LAI	I	7.390	0.0079	**
			A	0.164	0.6865	NS
	R6	LAI	I	0.555	0.4582	NS
			A	0.092	0.7623	NS
	V3	BM	I	8.638	0.0042	**
			A	0.199	0.6566	NS
	R1	BM	I	21.583	< 0.0001	***
			A	0.039	0.8439	NS
	R4	BM	I	24.519	< 0.0001	***
			A	0.000	0.9999	NS
Leaf area ratio	V3	RLA	q	6.196	0.0146	*
			A	0.063	0.8024	NS
	R1	RLA	q	13.310	0.0004	***
			A	0.038	0.8459	NS
	R4	RLA	q	18.703	< 0.0001	***
			A	0.022	0.8824	NS
	R6	RLA	q	0.034	0.8541	NS
			A	0.090	0.7649	NS

† Density, common ragweed density at harvest; BM, common ragweed aboveground biomass; LAI, leaf area index of common ragweed; NS, nonsignificant at $\alpha = 0.05$; RLA, common ragweed relative leaf area; V3, R1, R4, R6, soybean stage at destructive sampling.

‡ NS, nonsignificant; *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

in 2015 and 2016 and used to fit Eq. [3] resulted in *I* and *A* parameter estimates of 245 and 100, respectively (Fig. 4). The ME was 88 and RMSE was 200 (Fig. 4). The RMSE and ME indicated that the leaf area ratio model (Eq. [4]) fitted to common ragweed RLA at the R6 stage better fit the pooled data than the rectangular hyperbolic yield loss model (Eq. [3]) fitted to common ragweed LAI at the R6 stage.

Soybean Yield Loss

In 2015 and 2016, the average soybean yield in the weed-free control was 5177 kg ha^{-1} (SE ± 65) and 4422 kg ha^{-1} (SE ± 69), respectively. Equation [3] fitted to common ragweed density resulted in parameter *A* values of 100 in both years of this study. Equation [3] fitted to common ragweed density resulted in *I* parameter values of 159 and 33 in 2015 and 2016, respectively (Table 4). Common ragweed densities of 2, 6, and 12 plants m^{-1} row resulted in 76, 91, and 95% predicted soybean yield loss in 2015, respectively. The same common ragweed densities resulted in 40, 66, and 80% predicted soybean yield loss in 2016, respectively.

DISCUSSION

The results of this study indicate that the interference of common ragweed in soybean was driven by competition for light. Near adequate rainfall during the 2 yr of this study did not allow for the determination of the effects of varying soil water treatments. Therefore, varying soil water treatments had no effect on

Table 4. Comparison of AICc, k, AICw, ME, RMSE, I, and A for all model permutations tested where parameters varied between 2015 and 2016. Models are ordered from lowest to highest AICc with the lowest AICc considered the best fit and top model.†

Year	Stage	Method	AICc	AICw	ME	RMSE	I	A
2015	–	Density	312	0	98	34	159	100
	V3	BM	328	0	97	47	872	93
	R1	BM	311	0	98	38	43	96
	R4	BM	292	1	99	22	3.2	100
	V3	LAI	391	0	89	175	25709	96
	R1	LAI	320	0	97	40	2477	96
	R4	LAI	324	0	97	43	597	99
	V3	RLA	327	0	97	46	18279	93
	R1	RLA	320	0	97	40	3930	96
	R4	RLA	316	0	98	37	2198	97
2016	–	Density	357	1	92	87	33	100
	V3	BM	411	0	76	270	23	87
	R1	BM	387	0	85	163	4.5	100
	R4	BM	395	0	83	190	0.89	100
	V3	LAI	415	0	74	289	2168	89
	R1	LAI	390	0	85	171	319	100
	R4	LAI	404	0	79	230	150	100
	V3	RLA	400	0	81	211	1248	100
	R1	RLA	390	0	84	173	839	95
	R4	RLA	393	0	83	184	469	100

† A, asymptotic model parameter and maximum predicted yield loss; AICc, corrected information-theoretic model comparison criterion; AICw, model probability; BM, common ragweed aboveground biomass; Density, common ragweed density at harvest; I, initial slope model parameter and damage coefficient; LAI, leaf area index of common ragweed; ME, model efficiency; method, type of common ragweed measurement used as the independent variable; RLA, common ragweed relative leaf area; stage, soybean growth stage at which the sample was taken.

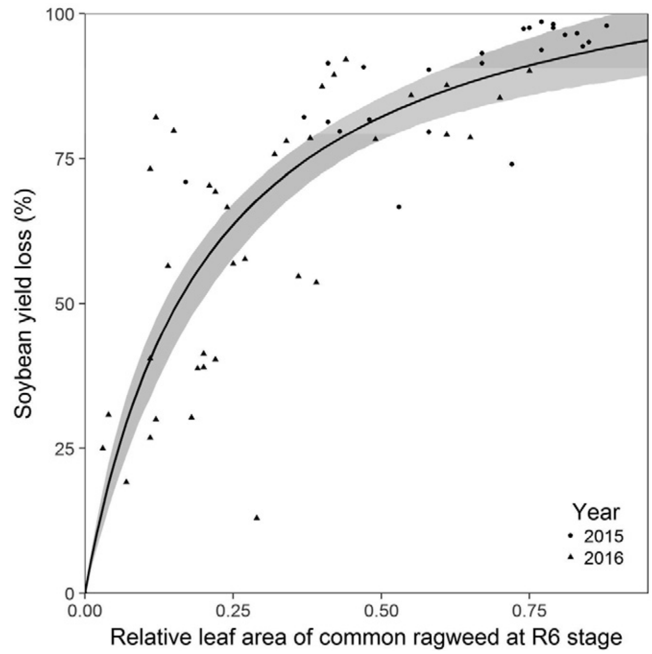

Fig. 3. Leaf area ratio model and 95% prediction interval fitted to yield loss (%) of soybean and common ragweed relative leaf area (RLA) sampled at R6 soybean growth stage in a field experiment conducted at the University of Nebraska-Lincoln in 2015 and 2016. Model parameters *A* (asymptote and maximum yield loss) and *q* (damage coefficient) were 96 and 562, respectively. The RMSE and modeling efficiency coefficient (ME) for this model were 159 and 91, respectively.

the model parameters during the 2 yr of this study, suggesting that soil water was not the most limiting factor. Although irrigation was never required before 25 Aug. in this study, Torrion et al. (2014) reported that soybean irrigation could be deferred until the R3 growth stage in soybean without a reduction in soybean yield. Unfortunately, soil water content never declined below 4.1 cm available soil water in the non-irrigated main plot, as predicted by SoyWater. Munger et al. (1987) reported that soybean water status was unaffected by velvetleaf (*Abutilon theophrasti* Medik) competition for soil water and that soybean extracted soil water from greater depths than that of velvetleaf. However, common cocklebur interference was reduced by increased drought stress (Mortensen and Coble 1989).

All model permutations explained soybean yield loss well within a year. However, late-season samplings (R6) of soybean and common ragweed leaf area provided the most robust predictor of soybean yield loss across years. The damage coefficients (*I* and *q*) varied for most model permutations, whereas maximum yield loss (*A*) did not vary for any model across years. Cowbrough et al. (2003) reported that parameters *I* and *A* in Eq. [3] fitted to soybean yield loss and common ragweed density differed between years in southern Ontario, Canada. Alternatively, Weaver (2001) reported that parameters *I* and *A* in Eq. [3] did not vary between years when soybean yield loss was fitted to common ragweed density in southern Ontario, Canada.

The rectangular hyperbola yield loss model (Eq. [3]) fitted to common ragweed LAI at the R6 stage effectively accounted for year-to-year variation in soybean-common ragweed interference. The hyperbolic yield loss model (Eq. [3]) parameters fitted to weed density have been reported to have considerable variation within a region and across years within a location in a regional study conducted on corn-weed interference (Fischer et al., 2004, Lindquist et al., 1996, 1999). Additionally, Eq. [3] lacks the ability to account for variation in the period between crop and weed emergence (Cousens et al., 1987; Kropff et al., 1995). The leaf area ratio model (Eq. [4]) fitted to the RLA of common ragweed at the R6 growth stage was the most robust predictor across years. Equation [4] accounts for year-to-year variation in weed and crop density, relative time of crop and weed emergence, and leaf area (Chikoye and Swanton 1995; Kropff et al., 1995). However, the ability to efficiently assess leaf area or RLA restricts the practical implementation of such models (Weaver 1991). Relative leaf cover has been reported to accurately estimate RLA and an efficient and precise method of estimating relative leaf cover could improve the applicability of such models (Lotz et al., 1994).

Parameter *I* estimates in relevant literature cannot be compared to this study due to differing units of the independent variable (Eq. [3]). Thus, it follows to compare soybean yield losses at particular common ragweed densities (Weaver 2001). In the present study, common ragweed densities of 1, 2, and 12 plants m^{-1} row resulted in 61, 76, and 95% predicted soybean yield loss (Eq. [3]) in 2015, respectively. The same common ragweed densities resulted in 25, 40, and 80% predicted soybean yield loss (Eq. [3]) in 2016, respectively. Equation [3] fitted to common ragweed density resulted in parameter *A* values of 100, implying that 100% yield loss could be achieved with increasing common ragweed densities. The predicted yield losses at equivalent common ragweed densities and the maximum yield loss

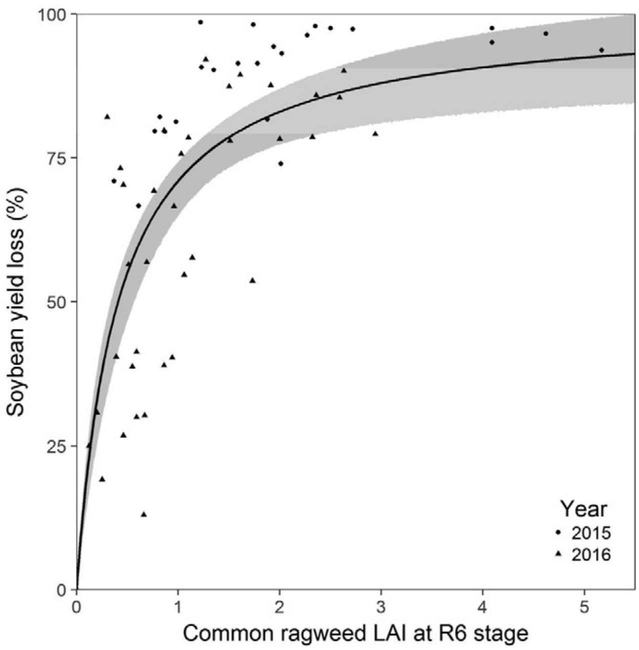

Fig. 4. Hyperbolic yield loss model and 95% prediction interval fitted to soybean yield loss (%) and common ragweed leaf area index (LAI) sampled at R6 soybean growth stage in a field experiment conducted at the University of Nebraska-Lincoln in 2015 and 2016. Model parameters *A* (asymptote and maximum yield loss) and *I* (initial slope and damage coefficient) were 100 and 245, respectively. The RMSE and modeling efficiency coefficient (ME) for this model were 200 and 88, respectively.

(Parameter *A*) in this study are greater than any other reported in the literature. At common ragweed densities of 1, 2, and 12 plants m^{-2} Cowbrough et al. (2003) reported predicted soybean yield losses of 22, 35, and 72% in 1999; and 9, 16, and 49% in 2000, and parameter *A* values of 92 and 84 in 1999 and 2000, respectively, in drilled soybean in southern Ontario using the rectangular hyperbolic yield loss model (Eq. [3]). At equivalent densities, Weaver (2001) reported predicted soybean yield losses of 12, 20, and 47% in 1991; and 5, 9, and 33% in 1993 and reported parameter *A* values of 65 and 71 in 1991 and 1993, respectively, in 60 cm soybean row spacing in southern Ontario using the rectangular hyperbolic yield loss model (Eq. [3]).

Common ragweed was more competitive with soybean in this study than studies reported in the literature (Coble et al., 1981; Cowbrough et al., 2003; Weaver 2001). Previous literature on soybean–common ragweed interference has not been reported in this region of North America. The greater yield losses observed in this study could be due in part to the methodology used for establishing common ragweed, where seeds were sown in a narrow band within the crop row, promoting competition for light at an early growth stage. It is possible the difference in time of common ragweed emergence relative to soybean emergence (6 and 0 d before) affected their interference relationships in the present study (Dieleman et al., 1995). Cowbrough et al. (2003) and Weaver (2001) reported lower soybean yield loss with 19 and 60 cm row spacing, respectively, compared with 76-cm row spacing in this study. Studies conducted with several other weed species report that narrow row spacing reduces soybean yield loss due to weed interference (Hock et al., 2006). Although studies have proposed potential effects of available soil water in wet versus dry years in crop–weed competition, due to plenty of rain during experimental years, it was not possible to detect the impact of soil moisture level in this study. More research is needed to determine the effects of variable soil water supply on soybean–weed interactions. A more thorough understanding of the relationship between soybean–weed competition and variable water would benefit future yield loss predictions.

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