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Soybean Yield Loss Potential Associated with Early-Season Weed Competition across 64 Site-Years

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Glyphosate applied POST can provide a high level of efficacy on many weed species in soybean, but delayed application beyond optimal weed growth stages might fail to fully protect yield potential. Further, we do not have a good understanding of the extent to which delayed glyphosate application and its associated yield loss is occurring on-farm. Our goal was to characterize on-farm weed communities in glyphosate-resistant soybean just prior to glyphosate application and estimate potential yield loss associated with early-season soybean-weed competition. In field surveys conducted across 64 site-yr in southern Wisconsin in 2008 and 2009, common lambsquarters, velvetleaf, dandelion, *Polygonum* spp., and *Amaranthus* spp. were the five most abundant broadleaf weed species across site-years, present in 92, 69, 64, 42, and 50% of all fields, respectively, at average densities of 14, 5, 5, 14, and 10 plants m^{-2}, respectively. Average height of these species was 21 cm or less at or near the time of glyphosate application. Grass and sedge species occurred in 95% of fields at an average density of 41 plants m^{-2} and height of 21 cm. The mean and median values of total weed density across site-years were 101 and 41 plants m^{-2}, with heights of 19 and 17 cm, respectively. Recommended height for treatment is 15 cm. Glyphosate application occurred on average at V3 to V4 soybean growth stage, which is later than V2 soybean typically targeted to protect yield. Average yield loss predicted by WeedSOFT® was 5% with a mean economic loss of \$47 ha^{-1}. Predicted yield loss was greater than 5% on one-fourth of the site-years, all of which were treated at V4 soybean or later. The maximum predicted yield loss was 27%. These results suggest that glyphosate was applied at weed height and soybean growth stages that were greater than optimal to protect yield in many fields across southern Wisconsin. A soil-residual herbicide applied PRE, or a more timely POST application of glyphosate would alleviate the majority of these losses.
Nomenclature: Glyphosate; *Amaranthus* spp.; common lambsquarters, *Chenopodium album* L. CHEAL; dandelion, *Taraxacum officinale* G. H. Weber ex Wiggers TAROF; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; *Polygonum* spp.; soybean, *Glycine max* (L.) Merr.
Key words: Decision support system, POST, weed abundance, weed community composition, WeedSOFT.

Total POST herbicide programs have become increasingly prominent since the release of glyphosate-resistant (GR) soybean in 1996 (Givens et al. 2009; Young 2006). Glyphosate-resistant soybean was rapidly adopted due to its low cost, high efficacy on most annuals and many perennials, flexible application timing, low environmental impact, and ease of use (Gulden et al. 2009; Krausz et al. 2001). In 2011, 94 and 91% of soybean acres in the United States and Wisconsin, respectively, were resistant to herbicides (USDA–NASS 2011a). In a survey of six states, Givens et al. (2009) found over 80% of GR soybean hectares were managed with glyphosate alone. In Indiana, Johnson et al. (2007) found 74% of survey respondents did not use residual herbicides in soybean. Thus, there has been the potential for more than 70% of all soybean hectares in the United States to be managed POST only with glyphosate.

Glyphosate applied alone can protect crop yields when compared to programs that include PRE herbicides (Gulden et al. 2009; Nurse et al. 2007). However, treatment or management must occur before the critical period of weed removal to prevent the potential for soybean yield loss (Eyherabide and Cendoya 2002; Halford et al. 2001; Knezevic et al. 2003; Sartorato et al. 2011). Previous research suggests the start of the critical period can range anywhere from the V1 to R1 soybean growth stage, corresponding with weeds approximately 10 to 80 cm in height, respectively (Coulter and Nafziger 2007; Knezevic et al. 2003; Mulugeta and Boerboom 2000; Sartorato et al. 2011). In most cases, glyphosate applied before V2 soybean protected yield. This corresponds approximately to treatment at weed heights of 15 cm or less (Coulter and Nafziger 2007; Dalley et al. 2004;). However, soybean planted in 76-cm row spacing might need to be controlled earlier, prior to V1 (Knezevic et al. 2003), to protect yield.

Yield loss due to late herbicide applications can be estimated using predictive models such as the decision support system WeedSOFT (Neeser et al. 2004). Yield loss predictions by WeedSOFT are based on the relative competitive indices among weed species, which are adjusted for crop growth stage, row spacing, weed height, and weed density. These values are then multiplied by the weed density and summed over all weed species to estimate the total competitive load, which is used to predict yield loss. The modifiers are specified for corn and soybean, and adjusted by state for Illinois, Indiana, Kansas, Michigan, Missouri, Nebraska, and Wisconsin (Neeser et al. 2004).

The accuracy of WeedSOFT predictions reflects the variability found in the critical period of weed control, which is relatively large, making the prediction of yield loss difficult. Hock et al. (2006) found WeedSOFT version 9.0 to have average errors in predicted soybean yield loss ranging from 0.05 to 17.06%. More recently, Jeschke et al. (2011) found WeedSOFT version 11 consistently overestimated soybean yield loss across a range of weed community emergence times, and was attributed in large part to overestimation of the competitive ability of giant and yellow foxtail [*Setaria faberi* Herrm. and *S. pumila* (Poir.) Roemer & J. A. Schultes].

Field surveys have been used to assess weed populations in a geographical region; however, to our knowledge they have not been used previously to characterize weed communities at the time of POST weed management. Thomas (1985) developed

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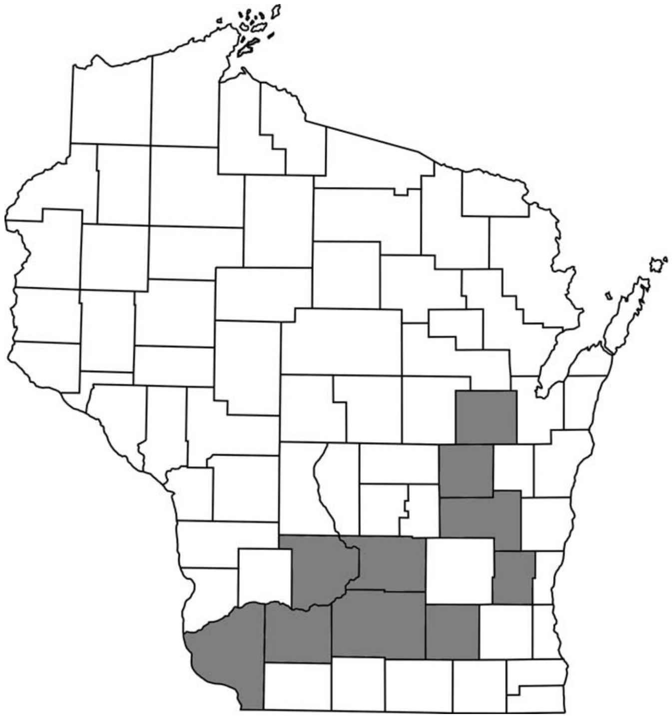

Figure 1. Wisconsin counties in which surveys of soybean field weed communities were conducted at the time of POST herbicide application in 2008 and 2009. Columbia, Dane, Fond du Lac, Jefferson, Outagamie, Washington, and Winnebago counties were surveyed in 2008 and 2009. Grant, Iowa, and Sauk counties were surveyed in 2009 only.

a weed survey system for cereal and oilseed crops in Saskatchewan. Similar surveys have also been conducted in Manitoba (Thomas and Dale 1991; Van Acker et al. 2000) and southwestern Ontario (Frick and Thomas 1992). However, these surveys (Frick and Thomas 1992; Thomas 1985; Thomas and Dale 1991; Van Acker et al. 2000) were conducted late in the growing season before harvest. Such weed surveys have not been conducted early enough in the growing season (i.e., before weed management) to quantify potential crop yield loss.

The use of survey methodology in combination with WeedSOFT makes it possible to assess potential yield loss for a large geographical area. The wide-spread adoption of GR soybean requires a change in weed management decision-making from that based on efficacy to one based on protecting crop yield potential, because high efficacy can be obtained while still allowing yield loss if glyphosate is applied too late. Our objective was to evaluate this potential by using surveys to characterize weed populations prior to weed management in southern Wisconsin soybean fields managed with POST herbicide programs, and by using WeedSOFT to predict associated yield loss. If substantial yield losses are predicted, this information could be helpful for improving the timeliness of POST herbicide applications, and thus protecting soybean yield.

Materials and Methods

Field Surveys. In 2008 and 2009, surveys were conducted in 64 soybean fields managed primarily with glyphosate across southern Wisconsin (Figure 1). In the area surveyed, about 170,000 ha of soybean are planted each year (USDA–NASS 2011b). This comprises 30% of soybean planted in the state of Wisconsin, and transects the major soybean growing areas. Fields were stratified by county within which three to seven fields were selected for surveying. Within a county, fields were selected based on three factors: a field had to be readily accessible by roadways, to be a minimum of 4.8 km from the nearest selected field, and to have an in situ weed plant community to ensure that POST weed control was yet to occur. Knowledge of prior weed control was not known; therefore, some surveyed fields might have received weed control treatment prior to POST weed control timing. Similarly, it is likely that some fields were not selected to be surveyed due to PRE weed control.

Field surveys were initiated when weed plant communities first became visible from the road. Knowledge of when glyphosate application would occur was not known. Thus, a selected field was typically surveyed every 3 to 4 d until the time of application, although some fields were surveyed weekly. During this time, soybean tissue was tested for resistance to glyphosate in each field using an enzyme-linked immunosorbent assay (Thomas et al. 2004). The last survey in each field occurred after glyphosate application, at which time crop height, crop growth stage, and row spacing were recorded.

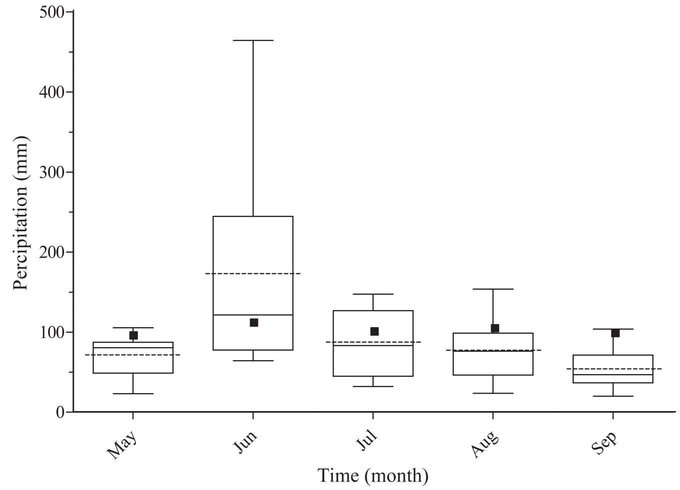

Figure 2. Monthly precipitation from May to September pooled over counties (Figure 1) and years in which surveys were conducted. The top and bottom of the box represent the third quartile and the first quartile, respectively. The median, or the second quartile, is the solid line through the box. The whiskers are vertical lines extending to the last data point within 1.5 times the interquartile range (the distance between the first and third quartiles) of the top or bottom of the box. Average monthly precipitation is designated by a dashed line (------). The 30-yr (1978 to 2007) average monthly precipitation for Columbia County in south central Wisconsin is designated by a black square (■).

Data Collection. Monthly precipitation and growing degree days (GDD) data were obtained by county for the 2008 and 2009 growing seasons from averages taken from daily National Oceanic and Atmospheric Administration cooperative stations (NOAA–NCDC 2010). These data were summarized for the months of May through September and compared to the 30-yr average of Columbia County (Figures 2 and 3), which was central to the region.

Weed communities were characterized following the methods of Thomas (1985) and Williams et al. (2008) with some modifications. Weed data were collected in 10, 1-m^2 quadrats spaced approximately 25 m apart along a horseshoe-shaped

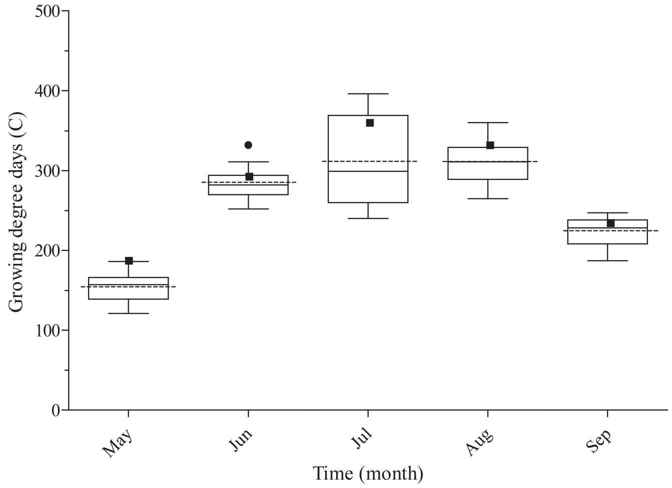

Figure 3. Monthly growing degree days (GDD) from May to September pooled over counties (Figure 1) and years (2008 and 2009) in which field surveys were conducted. GDD were calculated using a base temperature of 10 C and an optimum temperature of 30 C. The top and bottom of the box represent the third quartile and the first quartile, respectively. The median, or the second quartile, is the solid line through the box. The whiskers are vertical lines extending to the last data point within 1.5 times the interquartile range (the distance between the first and third quartiles) of the top or bottom of the box. Data points outside this range are designated by a black circle (●). Average monthly GDD is designated by a dashed line (------). The 30-yr (1978 to 2007) average monthly GDD for Columbia County in south central Wisconsin is designated by a black square (■).

pattern in each field. The first quadrat was located approximately 25 m from the field entry point. A consistent entry point into each field was maintained to ensure repeated sampling of the same weed community over time.

Within each quadrat, weed shoot height was measured and plant density was estimated using predetermined categories (Table 1). Most common weeds were identified by species, except for grasses and sedges, which were grouped due to the difficulty of identification at the seedling stage. Further, several broadleaf species were grouped within genera: *Amaranthus*, *Solanum*, *Plantago*, *Equisetum*, *Thlaspi*, and *Ranunculus*. Also, Pennsylvania smartweed (*Polygonum pensylvanicum* L.) and ladysthumb (*P. persicaria* L.) were grouped as smartweed species (*Polygonum* spp.). A minimum of the four most abundant species or species groups were surveyed if possible in each field to characterize weed community composition. Other weed species or species groups not surveyed, but observed in the field, were recorded as present. If a weed species could not be identified, a sample was collected for subsequent identification.

Data Analysis. Data for individual weed species or species groups were characterized using several quantitative measures (McCully et al. 1991; Thomas 1985; Williams et al. 2008). These included unadjusted and adjusted frequency, uniformity in all fields and in occurrence fields, density in all fields and in occurrence fields, height, and relative abundance. Unadjusted frequency represents the percentage of all fields in which a species was surveyed for height and density. Adjusted frequency represents the percentage of all fields where a species was recorded as present. Uniformity in all fields represents the percentage of total quadrats in all fields in which a weed species or group was surveyed. Uniformity in occurrence fields represents the percentage of quadrats in only those fields where the species was surveyed. Similarly, weed density in all fields represents the surveyed weed density averaged across all fields. Weed density in occurrence fields represents the surveyed weed density averaged across only those fields where density for a species or group was recorded. Because weed densities were estimated within categories of densities (Table 1), the midpoint of the density category was used to estimate average weed densities. For weed densities greater than 500 plants m^{-2}, average weed densities were based on a value of 750 plants m^{-2}. Height was weighted by the density for all calculations before being averaged across all quadrats where the species was surveyed, i.e., height for a species was multiplied by the density of that species within the same quadrat, summed across weighted heights, and then divided by the sum of the density. Relative abundance was a composite value calculated from the unadjusted frequency, the density in all fields, and the uniformity in all fields (Thomas 1985). This calculation assumed frequency, density, and uniformity were of equal importance. The resulting value for relative abundance is unitless, and when summed across all species equals 300. Relative abundance was used to assign a rank to each species.

Table 1. Weed height and density categories used for field surveys.

Height[a]	Density
cm	plants m^{-2}
0–5	0
6–10	1–5
11–15	6–10
16–20	11–50
21–25	51–100
26–30	101–500
> 30	> 500

[a] Height was the average for a species within the quadrat.

Box plot analyses were used to describe the data by site-year (Tukey 1977). The weed density for a site-year was calculated using density range midpoints averaged over all quadrats in the field, and summed over all surveyed species. The weed canopy height was weighted by density before being averaged over all species to give the mean overall weed height of a field. The box plot is comprised of five metrics, and separates the data into fourths for ease of viewing. Twenty-five percent of the data are below the lower or first quartile; 50% of the data are below the median or second quartile; whereas 75% of the data are below the third quartile. The complete data range is shown spanning from the minima to the maxima. GraphPad PRISM® version 5.03 (GraphPad Software, Inc., 2236 Avenida de la Playa La Jolla, CA 92037; http://www.graphpad.com/) was used to prepare all box plots, and to evaluate correlation between the weed density and the weed height using Spearman's rank correlation coefficient (Chikoye and Ekeleme 2003; Steel and Torrie 1980).

Predicted Soybean Yield Loss. Yield loss was predicted using WeedSOFT version 11.0.18 (WeedSOFT Decision Support System, University of Nebraska–Lincoln, P.O. Box 830915, Lincoln, NE 68583; http://weedsoft.unl.edu/) with modification. The basis of WeedSOFT calculations are the competitive index (CI) values assigned to weed species ranging from 0 to 10, with 10 being the most competitive. However, the surveyed weeds in our study included some species without designated CI values in WeedSOFT. To reduce the error of excluding these species from analysis,

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conservative CI estimates based on species of similar morphology were used (Table 2). Yield loss predictions were obtained on the per site-year basis using the modified WeedSOFT.

WeedSOFT uses the average density and height of each weed species in a field along with crop row spacing and growth stage as input to calculate a predicted yield loss (Neeser et al. 2004). In our research, weed species density was averaged over all quadrats. Average weed height was the height weighted by density averaged over all quadrats. Crop row spacing was a measured value for each field. Crop growth stage was that recorded when a field was observed as having received a herbicide application.

Predicted economic loss was calculated by modifying predicted yield loss using average county yield (2,800 kg ha^{-1} weighted average over county-years) and average state price (\$0.35 kg^{-1}weighted average over county-years) as published by the National Agricultural Statistics Service (USDA–NASS 2008, 2009). Current economic loss was calculated using the 2011 average state yield (3,100 kg ha^{-1}) and price per bushel (\$0.43 kg^{-1}) as published by the National Agricultural Statistics Service (USDA–NASS 2012a,b). Herbicide application costs were derived from the 2010 average cost of pesticide application (\$19 ha^{-1}) as published by the National Agricultural Statistics Service (USDA–NASS 2011c) and the 2011 herbicide costs as published by the University of Wisconsin–Extension (Cullen et al. 2011).

Results and Discussion

Site-Years. Yield loss estimates were made based on weed populations across 64 site-yr. Ninety-eight percent of these fields were shown to be planted to glyphosate-resistant soybean, based on enzyme-linked immunosorbent assays (data not shown). Row spacing included 19, 38, and 76 cm across site-years; 76 cm was the most common spacing. POST herbicide application on average occurred during late V3 to early V4 soybean growth stage (data not shown).

Weather. Precipitation (Figure 2) and GDD (Figure 3) for the 64 site-yr were less than the 30-yr average for Columbia County, WI, for most months. The exception was in June 2008, when a single rainfall event caused widespread flooding, and increased the average monthly precipitation to greater than the 30-yr average. For both precipitation and GDD, at least one county during 2008 and 2009 was above the 30-yr average and at least one was below it.

Weed Species Abundance. Fifty-one weed species were observed in 64 site-yr across southern Wisconsin in 2008 and 2009 (Table 2). Collectively, grass and sedge species were the most relatively abundant at 94.5, accounting for almost a third of the total relative abundance of 300. They occurred in 95.3% of fields and in 62.5% of all surveyed quadrats with an average height of 21 cm. Previous surveys suggest the most common grass and sedge species for south central Canada and north central United States are: fall panicum (*Panicum dichotomiflorum* Michx.), giant foxtail, green foxtail [*S. viridis* (L.) Beauv.], yellow foxtail, wild-proso millet (*Panicum miliaceum* L.), quackgrass [*Elymus repens* (L.) Gould], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (Frick and Thomas 1992; Jeschke et al. 2011; Williams et al. 2008).

Among broadleaf weed species, seven species had a relative abundance over 10. In order of most abundance, these were common lambsquarters, velvetleaf, dandelion, smartweed species, pigweed species (*Amaranthus* spp.), common ragweed (*Ambrosia artemisiifolia* L.), and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] with relative abundance values of 55.8, 26.2, 19.0, 18.6, 17.4, 15.8, and 11.1, respectively. Common lambsquarters was the most observed broadleaf species occurring in 92% of the fields and 54% of all the quadrats surveyed. Velvetleaf was the second most observed broadleaf species occurring in 69% of the fields and 28% of all the quadrats surveyed. Together common lambsquarters and velvetleaf accounted for 27% of total relative abundance, and 40% of relative abundance from broadleaf species.

Our weed abundance results were similar to those previously reported in other cropping systems. In a survey of grower's fields pooled over corn, soybean, and winter wheat fields in southwestern Ontario, Frick and Thomas (1992) found the most relatively abundant broadleaf weeds to be common lambsquarters, redroot pigweed (*Amaranthus retroflexus* L.), common ragweed, dandelion, pale smartweed (*Polygonum lapathifolium* L.), ladysthumb, and velvetleaf. Also pooled over a corn, soybean, and winter-wheat rotation in southwestern Ontario, Gulden et al. (2010) found the most frequently occurring broadleaf weeds on research stations to be common lambsquarters, dandelion, velvetleaf, pigweed species, and common ragweed. In 9 site-yr across the north central United States, Jeschke et al. (2011) found that weed communities in soybean consisted mostly of annual grass species (green and yellow foxtail) and moderately competitive annual broadleaf species (common lambsquarters, redroot pigweed, common ragweed, and velvetleaf). Aside from pale smartweed, which was not found in our study, the most abundant weeds in these previous reports were consistent with those in our study.

Our findings in soybean are also similar to those we observed for weed abundance in corn fields across southern Wisconsin (Fickett et al. 2013) where common lambsquarters, velvetleaf, dandelion, common ragweed, pigweed species, and shepherd's-purse were the most abundant species. In corn, the relative abundance of these species was 67.2, 35.1, 13.1, 12.6, 11.4, and 10.1, which were similar to values in soybean. The most notable difference between corn and soybean was abundance of smartweed species, which were less abundant in corn than soybean, with a relative abundance of 5.5 and 18.6, respectively. Also, common ragweed was more abundant than pigweeds in corn, which was not the case in soybean.

Some of the weeds that we found to be most abundant have been perceived as problematic by corn and soybean growers in Illinois, Indiana, Iowa, Mississippi, Nebraska, and North Carolina (Kruger et al. 2009). Following the adoption of a glyphosate-resistant corn and soybean rotation, velvetleaf was found to be the most problematic weed by 20% of growers. Relative to other weeds found in our survey, ragweed (*Ambrosia* spp.), common lambsquarters, and pigweed species were viewed as the most problematic by 13, 5, and 4% of the growers surveyed, respectively.

Weed Density and Height. Weed density and weed height were found to have no interaction (data not shown). The

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Table 2. Early-season weed species listed in order of relative abundance for 64 site-yr across southern Wisconsin in 2008 and 2009.

Rank	Common name	Latin name	Code	CI[a]	Frequency[b] Unadjusted	Frequency[b] Adjusted	Uniformity[c] All fields	Uniformity[c] Occurrence fields	Density[d] All fields	Density[d] Occurrence fields	Height[e]	Relative abundance[f]
					%				plants m^{-2}		cm	
1	Grass and sedge species			0.50[g]	89.1	95.3	62.5	70.2	36.5	41.0	21.0	94.5
2	Common lambsquarters	*Chenopodium album* L.	CHEAL	1.50	87.5	92.2	54.1	61.8	12.2	13.9	19.3	55.8
3	Velvetleaf	*Abutilon theophrasti* Medik.	ABUTH	1.00	56.3	68.8	28.3	50.3	2.9	5.2	20.5	26.2
4	Dandelion	*Taraxacum officinale* G. H. Weber ex Wiggers	TAROF	0.60	43.8	64.1	18.8	42.9	2.2	5.1	13.4	19.0
5	Smartweed species	*Polygonum* spp.		0.50	31.3	42.2	16.1	51.5	4.3	13.8	8.9	18.6
6	Pigweed species	*Amaranthus* spp.		0.90	35.9	50.0	13.4	37.4	3.6	10.1	10.5	17.4
7	Common ragweed	*Ambrosia artemisiifolia* L.	AMBEL	0.90	39.1	53.1	16.7	42.8	1.2	3.1	13.0	15.8
8	Shepherd's-purse	*Capsella bursa-pastoris* (L.) Medik.	CAPBP	0.25[g]	21.9	39.1	8.4	38.6	2.5	11.4	9.9	11.1
9	Nightshade species	*Solanum* spp.		0.25	17.2	26.6	4.7	27.3	0.2	1.4	10.7	5.5
10	Pennycress species	*Thlaspi* spp.		0.25[g]	7.8	14.1	4.2	54.0	0.4	5.6	18.4	3.8
11	Plantain species	*Plantago* spp.		0.25[g]	7.8	15.6	1.7	22.0	0.7	9.3	10.5	3.2
12	Corn speedwell	*Veronica arvensis* L.	VERAR	0.25[g]	7.8	7.8	3.3	42.0	0.2	2.5	10.4	3.1
13	Horseweed	*Conyza canadensis* (L.) Cronq.	ERICA	1.50	7.8	18.8	2.7	34.0	< 0.1	0.8	19.9	2.6
14	Canada thistle	*Cirsium arvense* (L.) Scop.	CIRAR	0.60	10.9	23.4	1.1	10.0	< 0.1	0.4	14.9	2.6
15	Giant ragweed	*Ambrosia trifida* L.	AMBTR	8.00	9.4	29.7	1.7	18.3	< 0.1	0.5	24.9	2.5
16	Marsh yellowcress	*Rorippa islandica* (Oeder) Borbas	RORIS	0.25[g]	1.6	1.6	0.8	50.0	1.1	71.5	8.3	2.2
17	Common mallow	*Malva neglecta* Wallr.	MALNE	0.25[g]	6.3	10.9	2.0	32.5	0.1	2.3	8.9	2.2
18	Common purslane	*Portulaca oleracea* L.	POROL	0.25[g]	3.1	9.4	0.9	30.0	0.5	17.3	10.1	1.7
19	Volunteer corn	*Zea mays* L.	ZEAMX	1.50[g]	6.3	14.1	0.9	15.0	< 0.1	0.5	30.5	1.6
20	Venice mallow	*Hibiscus trionum* L.	HIBTR	0.25[g]	3.1	3.1	1.6	50.0	0.2	6.8	6.0	1.5
21	Field bindweed	*Convolvulus arvensis* L.	CONAR	1.00	3.1	6.3	0.9	30.0	< 0.1	0.9	16.7	1.0
22	Prickly lettuce	*Lactuca serriola* L.	LACSE	0.25[g]	3.1	7.8	0.3	10.0	< 0.1	0.3	27.9	0.7
23	Common milkweed	*Asclepias syriaca* L.	ASCSY	0.20	3.1	9.4	0.3	10.0	< 0.1	0.3	33.0	0.7
24	Wild mustard	*Brassica kaber* (DC) L.C. Wheeler	SINAR	0.25[g]	3.1	4.7	0.3	10.0	< 0.1	0.3	15.2	0.7
25	Bull thistle	*Cirsium vulgare* (Savi) Ten.	CIRVU	0.70	3.1	6.3	0.3	10.0	< 0.1	0.2	20.3	0.7
26	Buttercup	*Ranunculus* spp.		0.20[g]	1.6	1.6	0.8	50.0	< 0.1	2.7	9.6	0.7
27	Prostrate knotweed	*Polygonum aviculare* L.	POLAV	0.25[g]	1.6	6.3	0.5	30.0	< 0.1	3.7	9.7	0.6
28	Common yarrow	*Achillea millefolium* L.	ACHMI	0.25[g]	1.6	1.6	0.5	30.0	< 0.1	1.9	58.8	0.5
29	White clover	*Trifolium repens* L.	TRFRE	0.25[g]	1.6	9.4	0.3	20.0	< 0.1	3.1	15.2	0.5
30	Hedge bindweed	*Calystegia sepium* (L.) R. Br.	CAGSE	0.60	1.6	3.1	0.3	20.0	< 0.1	1.1	25.4	0.4
31	Horsetail	*Equisetum* spp.		0.25[g]	1.6	9.4	0.2	10.0	< 0.1	0.8	35.6	0.4
32	Common burdock	*Arctium minus* (Hill) Bernh.	ARFMI	1.50[g]	1.6	6.3	0.2	10.0	< 0.1	0.3	10.2	0.4
33	White campion	*Silene latifolia* Poir.	MELAL	0.25[g]	1.6	15.6	0.2	10.0	< 0.1	0.3	10.2	0.4
34	Wild carrot	*Daucus carota* L.	DAUCA	0.25[g]	1.6	1.6	0.2	10.0	< 0.1	0.3	10.2	0.4
35	Jimsonweed	*Datura stramonium* L.	DATST	1.50	1.6	1.6	0.2	10.0	< 0.1	0.3	15.2	0.4
36	Yellow woodsorrel	*Oxalis stricta* L.	OXAST	0.25[g]	1.6	6.3	0.2	10.0	< 0.1	0.3	10.2	0.4
37–51	Other species[h]			< 0.1	≤ 10.9	1.6	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1

[a] CI was the competitive index used for a given weed.
[b] Frequency was the percentage of all fields where a species was surveyed for height and density (unadjusted) or the percentage of all fields where a species was recorded as present (adjusted).
[c] Uniformity was the number of quadrats where a species was surveyed divided by the total number of quadrats in all fields (all fields), or divided by the total number of quadrats in those fields where the species was surveyed (occurrence fields).
[d] Density was the number of plants m^{-2} either averaged across all fields (all fields) or averaged across fields where the species was surveyed (occurrence fields).
[e] Height was weighted by the density before being averaged across all quadrats in which the weed occurred.
[f] Relative abundance was a composite value calculated from the unadjusted frequency, the density in all fields, and the uniformity in all fields, which defined rank. The total value for the relative abundance of all species is 300.
[g] Competitive indices not included for Wisconsin in WeedSOFT version 11.0.18.
[h] Alfalfa, *Medicago sativa* L. MEDSA; birdsrape mustard, *Brassica rapa* L. BRSRA; black medic, *Medicago lupulina* L. MEDLU; common chickweed, *Stellaria media* (L.) Vill. STEME; common cottonwood, *Populus deltoides* Marsh. POPDE; common salsify, *Tragopogon porrifolius* L. TROPS; curly dock, *Rumex crispus* L. RUMCR; oakleaf goosefoot, *Chenopodium glaucum* L. CHEGL; rapeseed, *Brassica napus* L. BRSNN; red clover, *Trifolium pratense* L. TRFPR; Virginia copperleaf, *Acalypha virginica* L. ACCVI; wild buckwheat, *Polygonum convolvulu* L. POLCO; wild parsnip, *Pastinaca sativa* L. PAVSA; yellow fieldcress, *Rorippa sylvestris* (L.) Bess. RORSY; yellow rocket, *Barbarea vulgaris* Ait. f. BARVU.

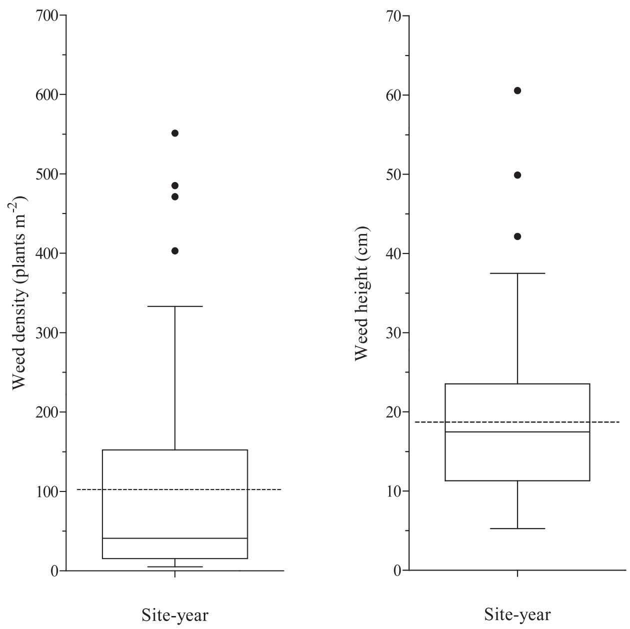

Figure 4. Weed community plant density and canopy height for 64 site-yr at the time of POST herbicide treatment pooled over counties (Figure 1) and years (2008 and 2009) in which surveys of soybean fields were conducted. The top and bottom of the box represent the third quartile and the first quartile, respectively. The median, or the second quartile, is the solid line through the box. The whiskers are vertical lines extending to the last data point within 1.5 times the interquartile range (the distance between the first and third quartiles) of the top or bottom of the box. Data points outside of this range are designated by a black circle (●). Average weed height and density are designated by a dashed line (------).

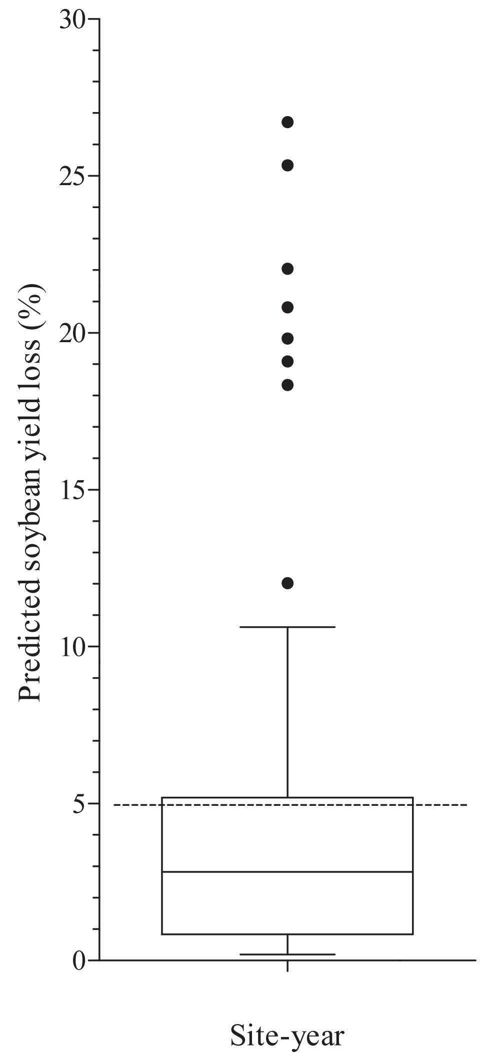

Figure 5. Predicted soybean yield loss for 64 site-yr at the time of POST herbicide treatment pooled over counties (Figure 1) and years (2008 and 2009) in which the field surveys were conducted. Yield loss was predicted using WeedSOFT version 11.0.18. The top and bottom of the box represent the third quartile and the first quartile, respectively. The median, or the second quartile, is the solid line through the box. The whiskers are vertical lines extending to the last data point within 1.5 times the interquartile range (the distance between the first and third quartiles) of the top or bottom of the box. Data points outside this range are designated by a black circle (●). Average predicted soybean yield loss is designated by a dashed line (------).

Spearman's rank correlation coefficient for weed density and height was -0.1565 with a 95% confidence interval of -0.3938 to 0.1002, which was not significant at $\alpha = 0.05$ ($P = 0.2167$) (data not shown). As such, weed density and weed height data were analyzed separately. At the time of removal, weed density ranged from 5 to 551 plants m^{-2} with a mean and median of 101 and 41 plants m^{-2}, respectively (Figure 4). The third quartile was at 152 plants m^{-2}. Weed height ranged from 5 to 61 cm at the time of removal with a mean and median of 19 and 17 cm, respectively (Figure 4). The third quartile was at 23 cm. Eleven site-yr, or 17% of all fields, were above the third quartile for both density and height, indicating that weeds were taller than 23 cm and densities greater than 152 plants m^{-2} at the time of weed removal. These values for weed density and height might be less than potential values because some fields might have received a PRE herbicide treatment prior to field selection.

Predicted Soybean Yield Loss. Over all 64 site-yr, predicted yield loss due to weed competition prior to glyphosate application ranged from 0.2 to 26.7% (Figure 5). The mean was greater than the median predicted yield loss with values of 5.0 and 2.8%, respectively. Eight outliers with yield loss values ranging from 12.0 to 26.7% contributed to the mean being greater than the median. The mean was equivalent to the third quartile of 5%, indicating that yield loss was greater than 5% at a quarter of the site-years. A yield loss of 5% in soybean represents a threshold often used for the critical period of weed removal (Knezevic et al. 2003; Sartorato et al. 2011). This implies that weed removal occurred after the start of the critical period of weed removal in a quarter or more of the surveyed fields.

Accuracy in predicting soybean yield loss is difficult due to the variability associated with specific conditions of early-season weed competition over locations and years. Weed control might be necessary starting when weeds are 10 cm tall, or in some instances, not until weeds are 80 cm tall (Coulter and Nafziger 2007; Knezevic et al. 2003; Sartorato et al. 2011). Research assessing WeedSOFT predictions of soybean yield loss from season-long competition suggests that predicted yield loss tends to be overestimated compared to observed yield loss (Jeschke et al. 2011). For weeds emerging at about the same time as soybean, Jeschke et al. (2011) found WeedSOFT predicted a season-long yield loss of 73%, when the observed yield loss was 40% across 9 site-yr. This overestimation of yield loss was attributed to the overestimation of the competitive ability of high densities of giant and

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yellow foxtail with soybean. However, the observed yield loss of 40% in Jeschke et al. (2011) suggests a much higher level of crop–weed competition than in our study (mean predicted yield loss of 5% across site-years). In corn, Schmidt et al. (2005) found predicted yield loss from WeedSOFT was an underestimate of observed yield loss when predicted yield loss was 10% or less, but was an overestimate of observed yield loss when predicted yield loss was greater than 20%. As such, we expect yield loss estimates in our study to be reasonably accurate, if not underestimates, of actual yield loss.

The predicted soybean yield losses in our study are consistent with previously reported empirical relationships among weed height or crop growth stage, and measured soybean yield losses. We found the average height of weeds to be 19 cm, which was taller than the recommended removal height of 15 cm, suggesting that yield loss is occurring in soybean fields across southern Wisconsin. In Illinois, Coulter and Nafziger (2007) found that weeds needed to be controlled between 11 and 19 cm to prevent yield loss greater than the cost of glyphosate application. Mulugeta and Boerboom (2000) found that initial weed control needed to occur before V2 to R1 soybean depending on row spacing (18 or 76 cm) and tillage (reduced-tillage or no-tillage) to prevent 3% yield loss. Knezevic et al. (2003) found that initial weed control needed to occur before V1, V2, and V3 soybean in 76-, 38-, and 19-cm row spacing, respectively, to prevent 5% yield loss. Recently, Sartorato et al. (2011) found that glyphosate applied once between V1 and R1 growth stages of soybean was sufficient to prevent significant yield loss (greater than 5%). In our study, 14 site-yr (22%) received treatment after the R1 growth stage of soybean (data not shown).

In our research, early-season soybean yield loss might have been affected by delays in herbicide application. Some potential causes for delay include weather, time constraints, and equipment availability. For example, during the 2008 growing season, high winds might have contributed to application delays in some site-years (N.D.F., personal observation). Applications based on efficacy outcomes rather than yield loss outcomes might also have caused delays (N.D.F., personal observation). Weed control must be made prior to the critical period of weed removal to prevent the potential of yield loss from early-season weed-crop competition (Knezevic et al. 2003; Sartorato et al. 2011). The criteria by which growers determine weed-control timing (e.g., fewest applications for high efficacy, timing by weed or crop height, or economic return) might be of interest for future research. It also could be of interest to determine which causes of delay (e.g., personnel or equipment availability, or weather) are most prevalent in forage-livestock or cash-grain operations. This information would facilitate the application of our research by allowing specific issues to be addressed.

The economic loss associated with the average predicted yield loss of 5% was \$47 ha^{-1} at the time the survey was conducted (data not shown). Yield loss was greater than 5% for 25 of the 64 site-yr. At 2011 crop prices, a 5% yield loss would be about \$66 ha^{-1} (USDA–NASS 2012a, 2012b). Glyphosate applied POST at the labeled rate (0.87 kg ae ha^{-1}) would cost about \$27 ha^{-1} at 2011 prices (Cullen et al. 2011; USDA–NASS 2011c), and would be equivalent to about 2% value of soybean yield per hectare. A PRE herbicide treatment would also be cost effective. Metribuzin applied PRE (0.27 kg ai ha^{-1}) at 2011 prices would cost about \$31 ha^{-1}, which is equivalent to about 2.3% of yield per hectare. In our study, predicted yield losses of 2.3% or more occurred for 56% of the site-years. This suggests that in many Wisconsin soybean fields, a two-pass program (PRE plus POST treatments) or earlier POST treatment timing might be economically beneficial.

The potential for yield loss in soybeans can be mitigated. Ellis and Griffin (2002) showed a residual herbicide applied PRE allowed the glyphosate application to be delayed 3 to 7 d. Similarly, Coulter and Nafziger (2007) found a PRE herbicide reduced weed interference when a POST herbicide could not be applied in a timely manner. Ivany (2004) found similar results with a single glyphosate application at late V2 to V3 soybean growth stages preventing yield loss, although with higher weed densities, a second application was sometimes beneficial. Additionally, several studies suggest that the wider the row spacing, the earlier the initial control needs to be, in order to prevent yield loss (Chandler et al. 2001; Knezevic et al. 2003; Mulugeta and Boerboom 2000), although Dalley et al. (2004) found wide rows to have lower but more consistent yield across herbicide application timings.

Although the potential for early-season yield loss can be reduced through timely application of glyphosate, we found that 17% of site-years were above the third quartile for both weed height and density, with weeds taller than 23 cm and densities greater than 152 plants m^{-2} at the time of weed removal. Also, we found 25% of site-years had predicted yield losses greater than 5%. Applying glyphosate before V4, or before weeds reach 23 cm would reduce yield loss in the highest risk fields. Further reduction in yield loss would be expected in some fields with initial glyphosate application prior to the recommended 15-cm weed height. This would have to be determined by the growers on a per field basis taking into account row spacing and weed density. Our results suggest that in many fields, a PRE herbicide or a late-POST glyphosate application integrated with the standard glyphosate POST application might be more economical than risking the predicted yield loss.

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