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Weed diversity and soybean yield with glyphosate management along a north–south transect in the United States

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There are many concerns about the effects of repeated use of glyphosate in glyphosate-resistant (GR) crops, including two that are seemingly contradictory. These are (1) weed escapes and (2) loss of weed diversity. Weeds that escape glyphosate treatment represent species that likely will become troublesome and difficult to control in the future, and identifying these future problems may allow more effective management. In contrast, complete weed control directly reduces the weed component of agroecosystem biodiversity and may lower other components indirectly (e.g., weed-dependent granivores). During 2001 and 2002 effects of glyphosate and conventional weed control treatments on weed community composition and GR soybean yields were studied. Field studies were conducted along a north–south transect of sites spanning a distance of 1600 km from Minnesota to Louisiana. Low-intensity use (single application yr^{-1}) of glyphosate allowed more escapes and maintained higher weed diversity than high-intensity use (two applications yr^{-1}) of glyphosate, and it was equivalent to or even higher than diversity in non-GR systems. Although the same weeds escaped from low- and high-intensity glyphosate treatments, frequency of escapes was higher with less intensive use. These results suggest that limited use of glyphosate would not have profound effects on weed diversity. In addition, crop yield did not differ between GR and non-GR treatments at high latitudes, but below 40° N latitude, with a longer cropping season, yields with low-intensity glyphosate use decreased by about 2% per degree latitude because of competition from escaped weeds.

Nomenclature: Soybean, *Glycine max* (L.) Merr.

Key words: Biodiversity, glyphosate resistance, glyphosate tolerance.

The rate of adoption of GR (glyphosate resistant) crops by farmers in countries that permit commercial GR crop production has outpaced the adoption of any other agricultural technology in history (Buttel 2002). In 2005, five principle countries were responsible for 95% of the total transgenic crop area: the United States, 55%; Argentina, 19%; Brazil, 10%, Canada, 6.7%; and China, 3.7%. GR soybean comprised 54 million ha, representing 60% of the entire transgenic crop area (James 2005). GR soybean has been adopted primarily for the simplicity of using a single herbicide, as well as its efficacy, lack of crop injury, lack of soil residual and potential injury to succeeding crops, and more flexible application timing than with conventional herbicides (Kudsk and Streibig 2003; Vitta et al. 2004). Despite rapid adoption by farmers, different voices from governments and nongovernmental organizations have opposed this technology. One fear of opponents of GR technology is the loss of biodiversity (Conner et al. 2003; Gould et al. 2003). The rationale for this opposition is that if GR crops replace conventional crops managed with traditional herbicides, then a substantial reduction may occur in resources provided by weeds to other organisms. Effects on field use by birds, for example, might be severe, because reductions in the abundance of weed seeds could represent a major loss of over-winter food resources (Robinson and Sutherland 2002; Watkinson et al. 2000).

Britain's Farm Scale Evaluations (FSE) showed different effects from transgenic crops on biodiversity. Growing conventional sugarbeet and canola was better for many groups of wildlife than growing herbicide-resistant varieties of these crops. Some insects, such as bees in sugarbeet (*Beta vulgaris* L. ssp. *altissima* DOELL var. *saccharifera* BECK.–DILL) and butterflies in sugarbeet and canola (*Brassica napus* L. var. *oleifera* MOENCH/DELL.), were recorded more frequently in conventional crops because there were more weeds in these crops to provide food and cover. There were also more weed seeds in conventional sugarbeet and canola than in their transgenic counterparts. In contrast, growing herbicide-resistant corn (*Zea mays* L.) was better for many groups of wildlife than conventional maize. The discrepancies between transgenic corn and transgenic canola and sugarbeet in the FSE imply that the differences may be attributable more to the timing of the spraying program than the genetic modification and use of the associated herbicide (DEFRA, 2003; Firbank et al., 2003; Giles, 2003).

Weed communities evolve in response to different agronomic practices and environmental factors (Frick and Thomas 1992). Effects of environmental and agronomic variables on demographic processes of a weed's life cycle must be known to understand the population dynamics of weeds (Ghersa et al. 2000). From long-term population studies, Doucet et al. (1999) concluded that weed management intensity, defined as herbicide application frequency, was more important than crop rotation in regard to changes in density and diversity of weed species. Relative to other control tactics, herbicides have a greater potential to select phenotypes that will persist after treatment by killing the more susceptible phenotypes in a population or by reducing their reproductive potential (Cousens and Mortimer 1995). Such distinct binary effects are not as apparent with other forms of control.

Prior to the introduction of GR soybean, glyphosate was used as a broad-spectrum treatment prior to crop emergence (Hydrick and Shaw 1994). Now that it is applied extensively postemergence within canola, corn, cotton (*Gossypium hirsutum* L.), and soybean, differential tolerance or resistance among weed species is reported with increasing frequency (Heap 2004, Norsworthy et al. 2001; Powles et al. 1998; Taylor, 1996; VanGessel 2001; Zelaya and Owen 2005). Some annual broadleaf species have varying levels of natural tolerance to glyphosate, e.g., common ragweed (*Ambrosia artemisiifolia* L.), velvetleaf (*Abutilon theophrasti* Medik.) (Kapusta et al. 1994), and morningglory (*Ipomaea* spp.) (Jordan et al. 1997), which has been one factor, among others, involved in weed species shifts with adoption of GR crops (Hilgenfeld et al. 2004). On the other hand, most grasses are usually quite susceptible to glyphosate (Wiesbrook et al. 2001).

Weed community composition is of agronomic significance because it will determine the type of required weed management strategies. Moreover, changes in weed diversity may be indicative of potential weed management problems (Derksen et al. 1995). Consequently, our research has focused on the effects of GR soybean technology on weed population composition, diversity, and crop yields throughout a portion of the soybean production area of the United States using otherwise conventional practices. The specific objectives were to identify the weeds most frequently present at harvest and to compare changes in weed diversity and crop yields in GR soybean systems with different levels of glyphosate management. Frequency is of interest as an indication of the magnitude of weed abundance and hence it is a good parameter to know what weeds could become troublesome and difficult to control in the future. GR systems also were compared with a soybean management system using conventional herbicides, including a now common recommendation to use residual soil-applied herbicides in combination with a postemergence glyphosate application. Effects of management systems were evaluated along a transect with a latitudinal range wide enough to encompass major gradients in weed biodiversity.

Materials and Methods

Field Experiments

During 2001 and 2002 weed management experiments were performed at different university research stations along a north–south transect across the soybean cropping area on the United States. The transect spanned 1600 km. The states and number of experiment stations included Minnesota (4), Iowa (3), Missouri (2), Arkansas (2), and Louisiana (1) in 2001. In 2002, the states (and sites) were Minnesota (4), Iowa (1), and Arkansas (1). All experiments were parts of much larger soybean herbicide screening trials within each state, and we attempted to select similar treatments across all sites. The experiments were carried out on experimental fields with natural populations of weeds. Specific treatments evaluated were as follows: (1) Weedy check. (2) Glyphosate applied once at 0.85 kg ae ha^{-1} when the tallest weed was about 15 cm and soybean growth stage was about V3 (three nodes and three trifoliate expanded leaves). This treatment was abbreviated as 1-Gly. (3) Glyphosate applied twice at 0.85 kg ha^{-1} when the tallest weeds were about 10 cm and again near the time of soybean canopy closure. This treatment was abbreviated as 2-Gly. (iv) Preemergence herbicides (metolachlor at 1.1 kg ai ha^{-1} and metribuzin at 0.26 kg ai ha^{-1}) plus glyphosate applied postemergence at 0.85 kg ha^{-1} at the same time as 1-Gly. This treatment was abbreviated PRE+Gly, and is often recommended by extension agronomists to maintain high soybean yields and to help forestall weed escapes and development of glyphosate resistance (Gunsolus et al. 2006). (v) Standard pre-emergence plus standard postemergence herbicides; i.e., the two-pass program that is the predominate commercial practice in the area. This treatment was abbreviated as Standard.

Each treatment was replicated four times and the experimental design in all the experiments was a randomized complete block. Although herbicides were applied independently at each experiment station, application specifications approximated the following: 3.1 m boom, 187 L ha^{-1} carrier volume of water, and a pressure of 207 kPa.

Experimental plots were seeded using conventional planters at about 400,000 seeds ha^{-1} in four rows spaced at 76 cm. Plots were 9.2 to 12.2 m long. Soils had been moldboard or chisel plowed and then disked, harrowed, or field cultivated for seedbed preparation. Planting occurred in mid to late May both years. Each plot was combine harvested, and soybean yield was calculated and expressed on the basis of 13% grain moisture. For each experiment, relative yield for a treatment was calculated as percentage of the maximum yield recorded on the experiment.

Data Collection and Diversity Indices

Density and coverage of weeds were measured for each treatment immediately prior to crop harvest. Both density and cover were assessed in six 0.1 m^2 quadrats placed along a diagonal line in each plot. Cover was estimated visually as percentage of soil surface covered by each plant species. Frequency of each species calculated as the percentage of sites in which the species was present in specific treatments. Frequency is a useful comparative index, especially in species-poor communities, as would be expected in herbicide-treated plots. In addition plot sizes were large enough to contain all species in agricultural communities (minimum 25 to 100 m^2) (Mueller-Dombois and Ellenberg 1974). Plot size in our experiments ranged from 28 to 37 m^2.

Diversity can be expressed by species richness, or the number of species present in a quadrat in relation to the number of individuals; species evenness, a measure of rela-

TABLE 1. Weeds species recorded at preharvest of the soybean crop in all the experiments and treatments from Minnesota to Louisiana (2001).

Weed species	L[a]–M[b]	1-Gly (Freq %)	2-Gly (Freq %)	PRE + Gly (Freq %)	Standard (Freq %)	Weedy (Freq %)
Chenopodium album L.	A–D	70	42	45	33	60
Solanum ptycanthum Dunal	A–D	60	42	36	25	30
Amaranthus spp. L.	A–D	60	33	18	33	70
Setaria spp. Beauv	A–D	60	25	27	50	50
Abutilon theophrasti Medik	A–D	50	8	18	8	30
Taraxacum officinale Weber	P–D	40	33	27	33	10
Ipomoea spp L.	A–D	30	42	36	42	40
Polygonum pensylvanicum L.	A–D	30	17	18	8	40
Sida spinosa L.	P–D	20	25	18	25	10
Physalis viscosa L.	P–D	20	8	9	0	10
Echinocloa crus-galli L.	A–M	10	25	0	17	50
Sesbania exaltata (Raf)	A–D	10	17	9	17	20
Panicum spp. L.	A–M	10	8	9	8	0
Cucumis melo L.	A–D	10	8	0	8	0
Agrostis tenuis Sibth	P–M	10	8	9	8	0
Digitaria sangunalis L.	A–M	10	8	0	8	10
Cyperus spp. L.	P–M	10	8	0	0	10
Cardus spp. L.	A–D	10	8	9	8	0
Solanum spp. L.	A–D	10	0	0	0	0
Ambrosia artemisiifolia L.	A–D	10	0	0	0	20
Xanthium strumarium L.	A–D	10	0	0	0	10
Phytolacca americana L.	P–D	10	0	0	0	0
Sorghum vulgare Pers.	A–M	10	0	0	0	0
Hibiscus trionum L.	A–D	10	0	0	0	10
Panicum miliaceum L.	A–M	10	0	9	8	10
Portulaca oleracea L.	A–D	10	0	0	0	0
Brachiaria platyphylla Griseb	A–M	0	8	0	8	20
Rumex crispus L.	P–D	0	0	9	8	0
Hordeum leporinum Link	A–M	0	0	9	0	0
Polygomum convolvulus L.	A–D	0	0	0	8	10
Asclepias syriaca L.	P–D	0	0	0	17	0
Sinapis arvensis L.	A–D	0	0	0	0	10

[a] L: life cycle—A, annual or P, perennial.
[b] M: Morphotype—D, dicotyledonous or M, monocotyledonous.

tive abundance of the species; or some combination of the two (Magurran 1988, cited in Doucet et al. 1999). Shannon diversity, H′, integrates both richness and abundance in a single value. A modification of H′ is effective species richness, or $e^{H'}$, which is equivalent to the number of equally common species required to produce the value of H′. In this work we have chosen effective species richness to describe weed diversity, which is calculated as follows:

$$\text{Shannons diversity index (H}') = \sum p_i \ln p_i \qquad [1]$$

where p_i is the proportion of individuals found in the ith species (Magurran 1998, in Doucet et al. 1999), and

$$\text{effective species richness} = e^{H'} \qquad [2]$$

Statistical Analysis

Numbers of species and diversity indices were analyzed by ANOVA. In each year, location was included as a factor in the analyses, and when the F test was significant ($P < 0.05$) means were separated by Fisher's protected LSD test 5%.

Results and Discussion

Floristic Composition and Frequency of Escapes

Over all experiments and treatments 32 and 21 weed species were recorded prior to crop harvest in 2001 and 2002, respectively. Combined over all treatments, locations and years, there were 42 annual and 11 perennial species. In addition, 40 were dicots and 13 were monocots (Tables 1 and 2). The highest number of weed species in 2001 was found in the 1-Gly treatment. In 2002, the same number of weed species was found in 1-Gly and in the weedy check (Figure 1).

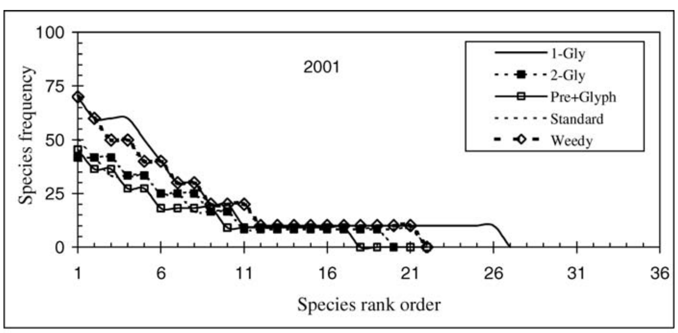
Weed management affected the frequency of weeds present at harvest. Figure 1 depicts frequency rankings of species that were found to escape management treatments from all experimental sites in 2001 and 2002 (Table 1 and 2). As expected, weed frequencies in the weedy check treatment are high, as no management other than crop competition suppressed weed growth. Interestingly, the 1-Gly treatment was equivalent to that of the weedy check and higher than that of other treatments. Weeds that escaped most frequently in the 1-Gly treatment were common lambsquarters (*Chenopodium album* L.), eastern black nightshade (*Solanum ptycanthum* Dun.), pigweed (*Amaranthus* spp.), foxtail (*Setaria*

TABLE 2. Weed species recorded at preharvest of the soybean crop in all the experiments and treatments from Minnesota to Louisiana (2002).

Weed species	L[a]–M[b]	1-Gly (Freq %)	2-Gly (Freq %)	PRE + Gly (Freq %)	Standard (Freq %)	Weedy (Freq %)
Amaranthus spp.	A–D	86	33	71	71	100
Chenopodium album L.	A–D	86	50	57	57	86
Solanum ptycanthum Dunal	A–D	57	50	14	29	71
Abutilon theoprasti Medik	A–M	43	0	14	0	43
Cirsium arvense L.	A–D	43	0	14	14	29
Polygonum pensylvanicum L.	P–D	43	33	14	43	43
Setaria spp. Beauv.	A–D	43	50	29	57	86
Ambrosia artemisiifolia L.	A–D	29	17	43	0	43
Echinocloa cruss-galli L.	P–D	29	0	29	29	43
Physalis viscosa L.	P–D	29	17	0	0	14
Xanthium strumarium L.	A–M	14	17	29	29	43
Brachiaria platyphylla Griseb	A–D	14	0	14	14	14
Digitaria sanguinalis L.	A–M	14	0	0	14	0
Setsbania exaltata (Raf)	A–D	14	0	14	0	14
Hibiscus trionum L.	P–M	14	0	0	0	0
Sida spinosa L.	A–M	14	0	14	14	14
Polygonum convolvulus L.	P–M	14	17	0	14	14
Solanum spp. L.	A–D	14	0	0	0	0
Ipomoea spp. L.	A–D	0	0	0	14	14
Asclepias syriaca L.	A–D	0	17	0	0	29
Panicum miliaceum L.	A–D	0	0	0	0	14

[a] L: life cycle—A, annual or P, perennial.
[b] M: Morphotype—D, dicotyledonous or M, monocotyledonous.

spp.), smartweed (*Polygonum* spp.), and velvetleaf. The same weeds represented the most frequent escapes in the 2-Gly treatment, but with lower values than in the 1-Gly treatment. For example, frequency of escape of common lambsquarters in 1-Gly was 70% in 2001 and 86% in 2002. In 2-Gly, these values were 42% in 2001 and 50% in 2002 (Tables 1 and 2). Frequency of different weeds is useful to indicate changes in weed species composition. Moreover, in this work it reflects the distribution of weeds that escape glyphosate compared with conventional treatments, regarding a large experimental area of the soybean crop area in the United States.



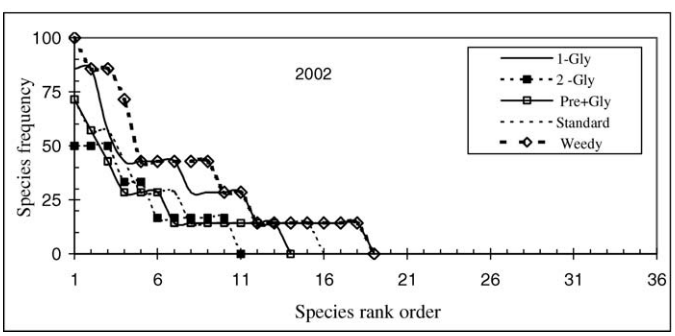


FIGURE 1. Frequency of weed species recorded in different treatments from all experiment stations in 2001 (top) and 2002 (bottom). For details of weeds see Tables 1 and 2.

Weed escape is an ever-growing concern with broad-spectrum burndown herbicides, like glyphosate, for growers who desire weed-free crops. Changes in species abundance will result in changes in the overall composition. Understanding the processes underlying weed species shifts is particularly important in determining the long-term sustainability of a management practice. Recognizing the mechanism is also valuable in designing integrated weed management practices that optimize herbicide use and prevent the evolution of resistance to a particular herbicide (Hilgenfeld et al. 2004). Understanding the differing ecological reasons for weeds escaping glyphosate, therefore, has great relevance. These reasons include germination that continues or begins after the last glyphosate application (Payne and Oliver 2000); morphological adaptations that reduce uptake and translocation of the herbicide, or large size at application time that confers tolerance to the herbicide (Mulugeta and Boerboom 1996; Norsworthy et al. 2001); and also in-row shielding by crops or weeds at the time of herbicide application. In addition, adverse growing conditions before and after herbicide exposure can restrict growth as well as the transport of herbicides to sites of action (Ruiter and Meinen 1998). Metabolic resistance and point mutations that alter the site of action of the herbicide also can explain individual tolerance to the herbicide (Westwood and Weller 1997; Yuan et al. 2002).

Delayed germination and emergence is, perhaps, one of the simplest explanations for escapes in glyphosate management systems. However, until emergence patterns of various weed species are studied and understood, we will not be able to determine the extent to which this demographic pro-

TABLE 3. Effective species richness ($e^{H'}$) for each treatment on different experiments in 2001.[a]

Experimental location	Standard	PRE + Gly	1-Gly	2-Gly	Weedy
Morris (MN)	1.3 b	1.2 b	3.4 a	0 b	1.5 ab
Lamberton (MN)	2.6 a	0.75 bc	3.8 a	0 c	2.5 ab
Waseca (MN)	1.7 ab	1.3 b	3.7 a	3 ab	3.1 ab
Potsdam (MN)	1.08	1.78	3.2	2.4	2.1
Ames (IA)	1 b	1 b	12.6 a	3.15 b	5.2 ab
Calumet (IA)	1.1	0.3	1.3	1.1	1.3
Crawfordsville (IA)	1.8 c	6 a	3.7 b	2.75 b	3.45 b
Columbia (MO)	[b]	[b]	13	3.8	[b]
Novelty (MO)	7.6	6.5	7.2	5.75	[b]
Colt (AR)	4.3 b	1.5 b	2.6 b	[b]	9.4 a
Keiser (AR)	1.5 c	2.5 b	4 a	[b]	4.4 a
Alexandria (LA)	2.2 ab	2.4 ab	3.3 a	1 b	1.8 ab

[a] Means within row followed by the same letter are not significantly different at P < 0.05 according to Fisher protected LSD test.
[b] Missing values.

TABLE 4. Number of weed species per plot for each treatment on different experiments in 2001.[a]

Experimental location	Standard	PRE + Gly	1-Gly	2-Gly	Weedy
Morris (MN)	1 b	1 b	2.75 a	0 b	3 a
Lamberton (MN)	2.25 ab	0.75 bc	3.5 a	0 c	4 a
Waseca (MN)	4 a	1.5 b	2.75 ab	3.25 ab	4 a
Potsdam (MN)	1.75 b	1.75 b	2.75 b	1.50 b	5 a
Ames (IA)	1 b	0 b	6.3 a	1.7 b	6 a
Calumet (IA)	2.3 b	1 b	2 b	2 b	7.3 a
Crawfordsville (IA)	3.7	5.7	4.7	3	4
Columbia (MO)	[b]	[b]	6.75 a	2.25 b	[b]
Novelty (MO)	5.75 a	4 a	5 a	3.25 a	[b]
Colt (AR)	4.75 a	1.75 b	2.5 b	[b]	5.75 a
Keiser (AR)	2.75 ab	2.5 b	3 ab	[b]	4.25 a
Alexandria (LA)	2.3 abc	2 bc	3.3 a	1.67 c	3 ab

[a] Means within row followed by the same letter are not significantly different at P < 0.05 according to Fisher protected LSD test.
[b] Missing values.

cess is governing weed escape from broad-spectrum burndown herbicides.

From our results, the most commonly observed species in glyphosate-treated plots were common lambsquarters, foxtail, and pigweed. Although they were never abundant or large enough to cause substantial losses in soybean yield, they were more abundant in the 1-Gly treatment than in the 2-Gly treatment. Scursoni et al. (2004) related the percentage of escapes with emergence at the time of glyphosate application and concluded that most of the individuals had escaped simply by avoiding contact with the herbicide. So the time of herbicide application in relation to emergence may be a key to herbicide effectiveness in terms of individual escapes.

Weed Diversity

The total number of weed species was higher in 2001 than in 2002 (Figure 1). In addition, species number in 2001 was higher in 1-Gly than in other treatments. In 2002, species numbers were similar for weedy and 1-Gly, and higher than that in the Standard, 2-Gly, and PRE+Gly treatments. Furthermore, treatments affected the frequency of species across sites. Frequencies of common species (rank order of 1–5) were considerably higher in Weedy and 1-Gly treatments than other treatments (Figure 1).

The highest weed densities at preharvest of the soybean crop were recorded on weedy check treatments (data not shown). However, this does not imply that this treatment had the highest diversity. Interestingly, 1-Gly showed high diversity, whereas 2-Gly and PRE+Gly (in both years) and standard herbicides (in 2001) exhibited low diversity when expressed as effective species richness (Table 3 and Figure 2).

In 2001, the number of weed species recorded per plot was significantly different between the weedy check and the 1-Gly treatment only in three of the experiments (Table 4). In 2002, there were significant differences between these treatments at Minnesota sites but not those in Iowa and Arkansas (Table 5). Weedy check treatments generally were dominated by one or two weed species, which lowered diversity values. The 1-Gly treatment suppressed dominant species and allowed the development of less common species, which manifested itself as high weed diversity in this treatment. In contrast, the 2-Gly treatment consistently decreased diversity to levels similar to the standard weed management treatment. A similar result was reported by Derksen et al. (1995) studying the effect of postemergence herbicides on weed community. Puricelli and Tuesca (2005) also documented that one glyphosate application during the crop cycle increased richness in different crop sequences owing to a progressive increase in density of late emergence annual broadleaf weeds.

In summary, the density and diversity of weeds remaining after control in soybean crops is neither lower nor higher

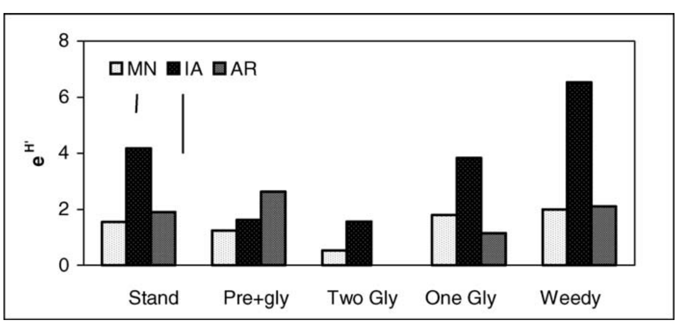


FIGURE 2. Effective species richness for different treatments as an average of all experimental sites in 2002. Bars inside indicate LSD (P < 0.05) between treatments.

TABLE 5. Number of weed species per plot for each treatment on different experiments in 2002.[a]

State	Standard	PRE + Gly	1-Gly	2-Gly	Weedy
Morris (MN)	1.75 b	0.75 b	1.75 b	1 b	4.5 a
Lamberton (MN)	2.25 ab	2.25 ab	2.75 ab	1 b	5 a
Waseca (MN)	2.25 b	2 b	2 b	0 c	3 a
Potsdam (MN)	3 b	2.5 b	2.75 b	0 c	6 a
Ames (IA)	3.7 abc	1.3 c	5 ab	2 bc	6 a
Colt (AR)	4.75	5	5.75	[b]	6.25

[a] Means within row followed by the same letter are not significantly different at P < 0.05 according to Fisher protected LSD test.
[b] Missing values.

with intensive use of GR technology than standard (conventional) weed management practices. Moreover, in plots less intensively managed with glyphosate (i.e., 1-Gly), diversity of weeds may be higher in comparison to conventionally managed crops. Greater diversity may be beneficial if high numbers of plant species is a management goal in GR crops, as it is in the United Kingdom (Firbank et al. 2003). However, a remaining question is whether higher weed diversity is related to higher weed/crop competition and higher crop yield losses. Integrated management strategies must be designed in order to maintain infestation levels compatible with economically and environmentally sustainable production. This depends on studies that reveal those strategies that make a plant population successful in a particular agroecosystem (Radosevich et al. 1997). The objective of weed management should be to reduce the impact of weeds on crop yield by maintaining a diverse community of controllable weed species (Clements et al. 1994) so that any one weed species that is difficult to control does not become dominant.

Crop Yield

Most farmers traditionally desire weed-free fields to ensure high yields and harvesting efficiency. Few farmers likely would adopt weed management schemes merely to enhance weed biodiversity but, as seen in the United Kingdom (Firbank et al., 2003), they might do this if crop yields were maintained at high levels. When soybean yields were plotted in relation to the latitude of experimental sites, there were no trends for the 2-Gly and pre-emergence herbicide followed by glyphosate treatments (Figure 3), as all yields were near 100% of the maximum for each experimental site. Similarly, there was no pattern for weedy checks. However, there was a significant correlation between the percent of maximum yield and latitude for the 1-Gly and Standard herbicide treatments (Figure 3). The apparent cut-off point for a 10% yield loss occurred at about 40° N latitude, about the border of Missouri and Iowa. This suggests that farmers can manage for rich assemblages of weeds with a one-pass glyphosate strategy while simultaneously maintaining high yields, but this is limited only to higher latitudes. Below 40° N latitude, yields in the one-pass glyphosate strategy decreased by about 2% per degree of latitude.

There are many factors to consider when using latitude as an index as in the above example. Seasonal weather, crop varieties, cropping practices, crop histories, and so forth all change with latitude, and all of these factors may have influenced the results of this study. Nevertheless, the results indicate that in Missouri and farther south, long growing seasons allow weeds that emerge and grow late to escape single glyphosate treatments and reduce crop yields substantially. However, in Iowa and farther north, single well-timed glyphosate applications inhibit weeds sufficiently to maintain high soybean yields, but still permit expression of high effective species richness and possibly the ecosystem services that accompany weed biodiversity. Thus, in north temperate agroecosystems, one-pass glyphosate management systems in GR crops may serve agronomic and environmental needs simultaneously.

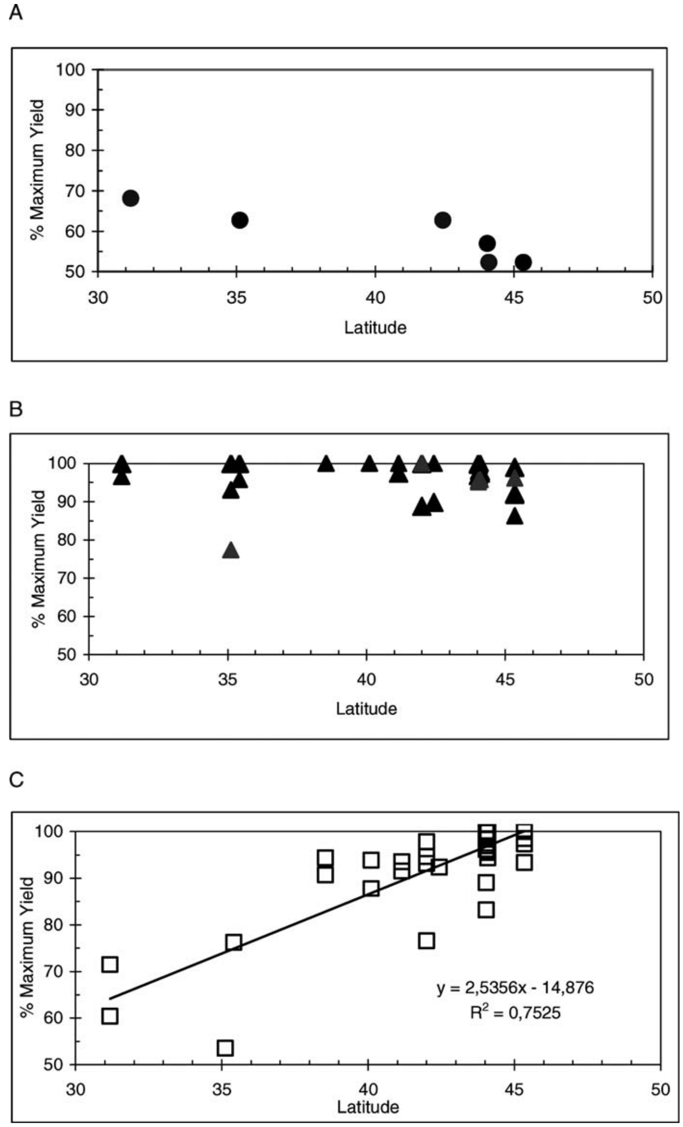


FIGURE 3. Relation between percent maximum yield and latitude of experimental sites for (A) weedy, (B) two-pass glyphosate and pre-emergence followed by glyhphosate, and (C) one-pass-glyphosate and standard treatments. Fitted model (2.54×-14.9) $r^2 = 0.75$.

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