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Does narrow row spacing suppress weeds and increase yields in corn and soybean? A meta-analysis

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Abstract

Narrow row spacing (<76 cm) could improve crop competitiveness, suppress weeds and might provide yield advantage. Many studies have been conducted to evaluate the impact of narrow row spacing; however, no quantitative synthesis of these studies exists. The objectives of this meta-analysis were to (1) quantify the overall effect of narrow row spacing (<76 cm) on weed density, biomass, control, weed seed production, and yield in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] compared with 76-cm row spacing, and (2) assess the influence of agronomic management decisions (tillage type, weed management, herbicide application frequency and time) on effect of narrow row spacing on weed suppression and corn and soybean yield. We compiled 1,904 pair-wise observations from 35 studies conducted in 12 states in the United States during 1961 to 2018. Averaged across individual observations, narrow row spacing suppressed weed density by 34%, weed biomass by 55%, and weed seed production by 45%, while it improved weed control by 32% and crop yield by 11% compared with 76-cm row spacing. Narrow row spacing in soybean suppressed weed density by 42%, weed biomass by 71%, and increased crop yield by 12% compared with 76-cm row spacing. Although narrow row spacing had a nonsignificant effect on response variables in corn, the number of studies ($n = 1$ to 6) and observations ($n = 1$ to 59) addressing each response variable were limited. Tillage type (conventional and reduced) did not influence the response of weed density, control, and seed production in narrow row spacing; however, weed biomass and weed seed production were more greatly reduced with the sequential application of herbicides compared with a single application. Thus, narrow row spacing in soybean can be integrated with other options for management of herbicide-resistant weeds.

Introduction

Row spacing is an important crop management tool to suppress weeds, optimize yields, and increase on-farm income. Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] are the most important row crops grown in the United States. Before the 1940s, row spacing in corn and soybean was wider (≥102 cm), as horses or other animals were frequently used for cultivation, limiting the feasibility of narrow row spacing (Olson and Sander 1988; Strand 1948). Narrow row spacing became popular with the advent of tractors replacing horses; the increasing availability of and advancements in machinery, irrigation technology, and hybrids that are lodging resistant and tolerant of dense stands; and the discovery of herbicides for selective weed management (Barr et al. 2013; Lehmann and Bateman 1944). Growers have adopted narrow row spacing (<102 cm) for better yield and resource-use efficiency. For example, 25 yr of field experiments in Illinois, Indiana, Iowa, Minnesota, and Ohio concluded that 53- to 71-cm row spacing in soybean increases yield by 15% compared with the 102- to 107-cm row spacing that was most common in the Corn Belt during the 1960s (ASA 1966). Likewise, in Minnesota, row spacing in corn decreased from 107 cm in the 1930s to 90 cm in 1979, contributing to a 4% increase in yields (Cardwell 1982).

In the past several decades, researchers and growers have begun showing interest in row spacing less than 76 cm, particularly for soybean, because the yield advantages are more consistent for soybean than corn (Lauer 1996; Licht 2018). In Iowa, the average row spacing in soybean decreased from 84 cm in 1980 to 56 cm in 2000 and 60 cm in 2020, whereas the average row spacing in corn decreased from 90 cm in 1980 to 81 cm in 2000 and 76 cm in 2020 (USDA

1981; USDA-NASS 2001, 2021). In narrow row spacing, plants have more equidistant distribution, which reduces intra-plant competition for light, water, and nutrients, leading to higher yields than in wider row spacing. Although yield advantages are the primary driving force for growers, narrow row spacing provides additional advantages, such as reducing soil erosion (Mannering and Johnson 1969) and evaporative water loss (Sharratt and McWilliams 2005) and suppressing weeds (Bradley 2006). The crop canopy closes earlier in narrow row spacing. For instance, Esbenshade et al. (2001b) reported that soybean in Pennsylvania with 38-cm row spacing closed its canopy 19 d before soybean with 76-cm row spacing. Similarly, in Nebraska, soybean with 25-cm row spacing reached full canopy closure 22 d before 76-cm row spacing (Burnside and Colville 1964). Likewise, soybean with 19-cm row spacing closed its canopy 20 d earlier than soybean with 76-cm row spacing in Nebraska (Hock et al. 2006) and Missouri (Carey and Defelice 1991), 30 d earlier in Illinois (Wax and Pendleton 1968), and 35 to 45 d earlier in Michigan (Mickelson and Renner 1997; Nelson and Renner 1998). Early crop-canopy closure increases light interception (Steckel and Sprague 2004; Taylor et al. 1982; Tharp and Kells 2001), crop growth, and competitiveness (Hock et al. 2006; Murphy et al. 1996; Rich and Renner 2007) and thus suppresses weeds due to shading effects (Buehring et al. 2002; Nice et al. 2001). In contrast, in wider row spacing, more light reaches the soil surface, permitting weeds to emerge or regrow later in the season (Datta et al. 2017; Yelverton and Coble 1991). Therefore, soybean and corn planted in ≥76-cm row spacing often require weed control for longer periods to avoid yield loss compared with soybean and corn planted in narrow row spacing (Knezevic et al. 2003; Mulugeta and Boerboom 2000; Nedeljković et al. 2021; Rosset and Gulden 2020).

Weed suppression with narrow row spacing in corn and soybean has been studied and well documented (Bradley 2006; Datta et al. 2017; Mhlanga et al. 2016). As with the yield benefit, the weed suppression provided by narrow row spacing has been found more frequently in soybean than in corn. Bradley (2006) reported improved late-season weed control (density and/or biomass) in 64% of case studies (72 out of 113 site-years) in soybean and 24% of case studies (12 out of 50 site-years) in corn. Although Bradley (2006) summarized the results of independent studies, there is no systematic and quantitative synthesis of the literature existing on this topic in corn and soybean. Therefore, the objectives of this meta-analysis were to (1) quantify the overall effect of narrow row spacing (<76 cm) on weed density, biomass, control, weed seed production, and yield in corn and soybean compared with 76-cm row spacing, and (2) assess the influence of agronomic management decisions (tillage type, weed management, and herbicide application frequency and time) and narrow row spacing on weed suppression and crop yield.

Materials and Methods

Literature Search, Selection Criteria, and Data Extraction

An extensive literature search was performed during January to June 2022 using predetermined key words in the Google Scholar and Scopus databases as well as two weed science journals: *Weed Science* and *Weed Technology*. The key words "row spacing" AND "corn" OR "maize" OR "soybean" were searched in Google Scholar, "row spacing" AND "weed control" OR "corn" OR "maize" OR "soybean" were searched in Scopus, and "row spacing" OR "row width" were searched in the *Weed Science* and *Weed Technology* journals. The search queries were targeted at article titles and resulted in 2,013 total hits, from which 35 relevant articles were identified following a multistep protocol (Figure 1). The relevant articles were selected based on predetermined inclusion criteria: (1) field study from the United States, (2) corn and/or soybean row-spacing treatments of 76 cm and under (even row-spacing treatments >76 cm were included for the meta-regression analysis), and (3) reported treatment and control means for at least one response variable (i.e., weed density, weed biomass, weed control, weed seed production, and corn/soybean yield). From the selected 35 relevant articles, the following information was extracted:

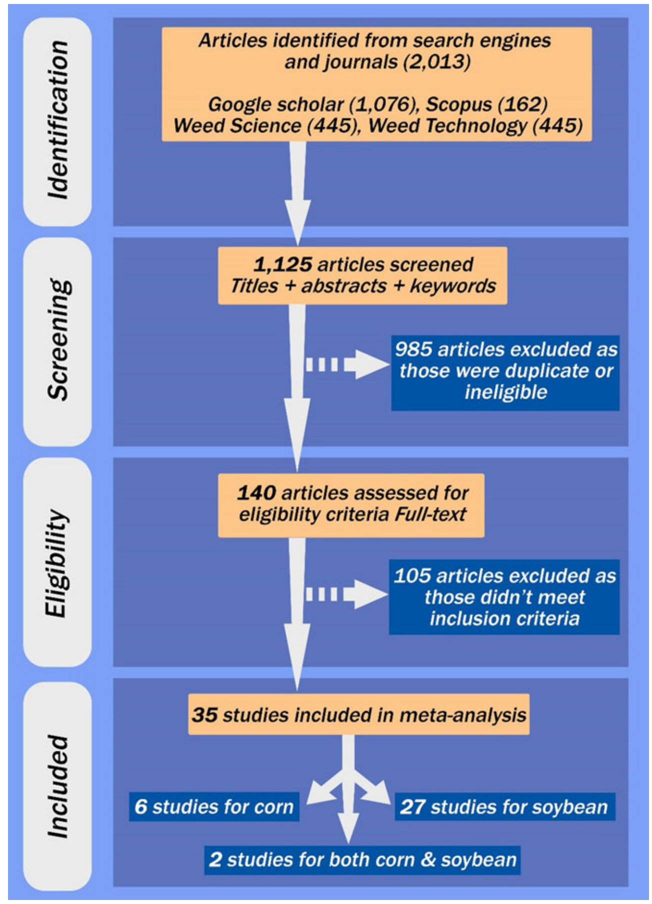

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Page et al. 2021) flow diagram showing the stepwise procedure used for selecting 35 studies for meta-analysis.

- weed-related information (common name, scientific name, and weed type);
- crop or crop management–related information (cash crop, plant population, tillage type, weed management, and frequency and time of herbicide applications);
- soil-related information (soil series, soil texture, soil pH, and organic matter);
- experiment-related information (study location, experimental year, number of replications, row-spacing treatments, and days after planting for recorded observations); and
- weed or crop response–related information (observation means for treatment and control groups for each response variable: weed density, weed biomass, weed control, weed

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seed production, and crop yield), with a row spacing of 76 cm considered to be the control group and all other row spacing to be the treatment group.

Finally, we extracted a total of 1,904 observations across all response variables from the 35 published papers.

Meta-analysis: Overall Effect of Narrow Row Spacing on Weed Suppression and Crop Yield

The overall effect of narrow row spacing (< 76 cm) on weed suppression and crop yield was calculated using the natural logarithm of response ratios (Hedges et al. 1999) (Equation 1):

$$\overline{\ln(RR)} = \ln(\bar{X}_{\mathrm{RS}}/\bar{X}_{\mathrm{C}}) = \ln(\bar{X}_{\mathrm{RS}}) - \ln(\bar{X}_{\mathrm{C}}) \quad [1]$$

where $\overline{\ln(RR)}$ is the natural logarithm of response ratios and refers to the individual effect sizes, $\bar{X}_{\mathrm{RS}}$ and $\bar{X}_{\mathrm{C}}$ are mean values for specific response variables (i.e., weed density, weed biomass, weed control, weed seed production, and crop yield) for the treatment (i.e., narrow row spacing < 76 cm) and control (i.e., 76 cm) groups, respectively. Observations with zero values for response variables were replaced with the minimum possible values (e.g., 0.1% for 0% weed control, 0.1 g for 0 g weed biomass). This is because response ratios cannot be calculated if the treatment value is zero (Singh et al. 2022; Thapa et al. 2018a).

Most of the studies included in meta-analysis did not report measures of within-study variability such as standard error (SE), standard deviation (SD), or the coefficient of variation (CV). This limits the weighting of individual effect size using the standard variance approach of Hedges and Olkin (2014). Therefore, the individual effect sizes were weighted using experimental replications as proposed by Adams et al. (1997) (Equation 2):

$$w_i = (N_{\mathrm{RS}} \cdot N_{\mathrm{C}})/(N_{\mathrm{RS}} + N_{\mathrm{C}}) \quad [2]$$

where w_i denotes the weight of individual effect size, N_{RS} is the number of replications for the treatment group, and N_{C} is the number of replications for the control group.

If the published research article reported data from experiments conducted over multiple site-years or included multiple row-spacing treatments that shared the common control group, more than one effect size was calculated. However, this may result in non-independent effect sizes within and among the studies. To account for non-independence among individual effect sizes, a multilevel mixed-effects meta-analysis model was created using the NLME package in R (see Supplementary Materials for the R code) (Pinheiro et al. 2023; Singh et al. 2022; Thapa et al. 2018b; Van den Noortgate et al. 2013). In this model, effect sizes were included as a fixed effect, site-year/common control treatments were included as nested random effects, and w_i values acted as weighting factors. Furthermore, robust SEs for the weighted mean effect sizes were calculated using a cluster-based robust variance estimator with the CLUBSANDWICH package in R (Pustejovsky 2022). These robust SEs were used to calculate 95% confidence intervals (CIs) of weighted mean effect sizes, that is, $\overline{\ln(RR)}$. Whenever 95% CIs of the weighted mean effect sizes did not include zero ($P < 0.05$), the treatment effect on a particular response variable was considered significantly different from that of the control group. To interpret results simply, $\overline{\ln(RR)}$ values and their corresponding 95% CIs were exponentially back-transformed to percent change in response variables (Equation 3):

$$\%\ \text{change in response} = \left[e^{\overline{\ln(RR)}} - 1\right] \times 100 \quad [3]$$

where $\overline{\ln(RR)}$ is the weighted mean effect size for each response variable.

Moderator Analysis: Effects of Cash Crop, Tillage, Weed Type, Weed Management, and Herbicide Application Frequency and Time on Overall Narrow Row Spacing Effects

A moderator analysis was conducted to test how overall effect sizes were affected by potential covariates such as type of cash crop, tillage, weed type, method of weed management, and the frequency and time of herbicide applications. Each covariate was differentiated into two or more subgroups:

- cash crop: 'corn' or 'soybean';
- tillage: 'conventional' or 'reduced';
- weed types: 'grasses', 'broadleaves', or 'mixed' (both grasses and broadleaves);
- methods for weed management: 'herbicide' treatment plots, 'untreated or weedy' plots with no use of herbicides, or 'weed-free' control plots;
- frequency of herbicide applications: 'single' or 'sequential'; and
- herbicide application time: 'PRE', 'POST', 'PRE fb POST', or 'POST fb POST'.

Individual effect sizes were calculated with robust SEs for each subgroup. Each moderator variable was used as a sole covariate in the primary multilevel mixed-effects meta-analytic model explained earlier. The 99% CIs were calculated to lower the chances of experiment-wise type I errors. The mean effect of narrow row spacing was considered significant ($P < 0.01$) when 99% CIs of each subgroup did not contain zero; they were considered significantly different from one another when there was no overlap of their 99% CIs (Singh et al. 2022; Thapa et al. 2018a).

A meta-regression analysis was performed for each response variable to determine the relationship between individual effect size and row spacing of treatment groups. For this analysis, treatment groups with row spacing greater than the standard row spacing of 76 cm were also included for control groups.

Publication Bias and Sensitivity Analysis

As previously noted, most of the studies did not report sampling variances. This prevented the creation of meaningful funnel plots to test publication bias. Therefore, an alternative, indirect, and visual approach was used in which density plots were used to assess the distribution of individual effect sizes for each response variable (Basche and DeLonge 2017; Singh et al. 2022; Thapa et al. 2018a). When creating density plots, imputed effect sizes (i.e., effect sizes where observed zero values were replaced with minimum possible values) were excluded. Overall effect sizes were tested for robustness. The jackknife procedure was used for sensitivity analysis to identify studies that might have influenced the overall effect sizes (Philibert et al. 2012). This involved a stepwise exclusion of one study at a time from the database, followed by rerunning the primary multilevel mixed-effects meta-analysis model each time to recalculate individual effect sizes.

Results and Discussion

Database Description

A total of 1,904 pair-wise observations (1,696 pairs of narrow row spacing (< 76 cm) and 208 pairs of wider than 76 cm row spacing; 91 and 102 cm) were extracted from 35 studies that were conducted during 1961 to 2018 in the United States (Table 1). These studies were conducted in 12 states, with more than one-fourth ($n = 29$ out of 35) of studies conducted in the nine midwestern states (Figure 2), including nine studies in Michigan, seven in Nebraska, four in Illinois, three in Missouri, and two in Wisconsin (Table 2). Among other midwestern states, one study each was conducted in Iowa, Indiana, Kansas, and Minnesota. Outside the Midwest, three studies were conducted in Mississippi, two in Pennsylvania, and one in Delaware. Out of 35 studies, 6 studies included corn, 27 included soybean, and 2 studies included both corn and soybean.

The data were collected either on individual broadleaf ($n = 22$) or grass ($n = 7$) weed species or a mixture of both ($n = 16$) (Table 1). These weed species belonged to 12 families: Amaranthaceae, Asteraceae, Brassicaceae, Chenopodiaceae, Convolvulaceae, Cucurbitaceae, Fabaceae, Malvaceae, Poaceae, Polygonaceae, Portulaceae, and Solanaceae. Among broadleaf weed species, the most evaluated species was waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], which was evaluated in six studies; followed by velvetleaf (*Abutilon theophrasti* Medik.) in five studies; common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) in four studies each; common ragweed (*Ambrosia artemisiifolia* L.) and sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby] in three studies each; and burcucumber (*Sicyos angulatus* L.), common cocklebur (*Xanthium strumarium* L.), eastern black nightshade (*Solanum ptychanthum* Dunal), and Palmer amaranth (*Amaranthus palmeri* S. Watson) in two studies each. Canada thistle [*Cirsium arvense* (L.) Scop.], common sunflower (*Helianthus annuus* L.), giant ragweed (*Ambrosia trifida* L.), hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], horsenettle (*Solanum carolinense* L.), ivyleaf morningglory (*Ipomoea hederacea* Jacq.), and pitted morningglory (*Ipomoea lacunosa* L.) were each evaluated only once (Table 2). Among grass weed species, giant foxtail (*Setaria faberi* Herrm.) was evaluated most often (in five studies) followed by barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] in two studies. Fall panicum (*Panicum dichotomiflorum* Michx.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.] were studied only one time each.

In terms of tillage, 11 studies employed conventional tillage, 13 employed reduced tillage (Table 1), 6 employed both conventional and reduced tillage (Bowman et al. 1986; Burnside and Colville 1964; Mickelson and Renner 1997; Nelson and Renner 1999; Wax and Pendleton 1968; Young et al. 2001), and 5 studies did not use or provide any information on tillage (Bailey et al. 2015; Harder et al. 2007; Hay et al. 2019; Knezevic et al. 2003; Moomaw and Martin 1984). The data-fitting inclusion criteria were extracted irrespective of whether those observations were from untreated/weedy treatments or with the use of herbicides. In this data set, 11 studies used herbicides, 9 did not, and 15 studies used both herbicide and untreated/weedy treatments. The studies that used herbicides had either single ($n = 12$), sequential ($n = 2$; Schultz et al. 2015; VanGessel et al. 2003), or both single and sequential herbicide applications ($n = 10$). These applications were either PRE ($n = 3$; Burnside and Colville 1964; Moomaw and Martin 1984; Wax and Pendleton 1968), POST ($n = 9$), PRE fb POST ($n = 1$, VanGessel et al. 2003), POST fb POST, or combinations of these three ($n = 10$).

Effects of Narrow Row Spacing on Weed Density

Averaged across 107 pair-wise comparisons from 11 studies, narrow row spacing (<76 cm) reduced overall weed density by 34% (Figure 3; 95% CI = −54% to −5%), with only a significant reduction of 42% in soybean (99% CI = −63% to −9%) but not in corn (Figure 4A). This is consistent with the review from Bradley (2006), who reported the late-season benefits (i.e., reduced weed density, and/or biomass or improved weed control) of narrow row spacing (<76 cm), often in soybean (64% instances; $n = 72$ out of 113 site-years) but occasionally in corn (24% instances; $n = 12$ out of 50 site-years). Meta-regression analysis further indicates that the overall effect sizes of weed density were positively correlated with crop row spacing, with a low degree ($R = 0.38$) of high statistical significance ($P < 0.001$) (Figure 5A). This suggests that weed density was reduced to a lower degree with increasing row spacing: for example, Harder et al. (2007) observed that weed emergence decreased significantly 3 wk after glyphosate application (on 10-cm weeds) in 19-cm (5 plants m^{-2}) soybean row spacing, but not in 38-cm (8 plants m^{-2}) compared with 76-cm row spacing (12 plants m^{-2}). A notable point from Figure 5A is that observations for soybean had only 19-cm ($n = 34$) and 38-cm ($n = 60$) row-spacing treatments, while corn had mostly 51-cm ($n = 11$) and 91-cm ($n = 36$) row-spacing treatments, except for two observations for 38-cm row spacing. This explains in part the nonsignificant effect of narrow row spacing (<76 cm) on weed density in corn, as more than one-fourth of observations ($n = 11$ out of 13) came from relatively wider row spacing (51 cm) compared with 38 cm, where weed density was not affected. In contrast, soybean row spacing was narrower (19 and 38 cm), and a higher reduction in weed density was evident with narrower row spacing (i.e., 19-cm row spacing compared with 38-cm row spacing). Reduced weed densities, especially of species that emerge later in the season, are primarily attributed to increased light interception (Hay et al. 2019; Puricelli et al. 2003; Steckel and Sprague 2004) and earlier crop-canopy closure (Burnside and Colville 1964; Hock et al. 2006; Légère and Schreiber 1989; Mickelson and Renner 1997; Nelson and Renner 1998; Peters et al. 1965; Rich and Renner 2007; Wax and Pendleton 1968) found in narrower row spacing (Bradley 2006).

Although narrow row spacing reduced weed density, effects were not significant for tillage (conventional and reduced), weed type (grass and mixed), weed management (herbicide and no-herbicide), herbicide application frequency (single and sequential), and time (PRE, POST, and POST fb POST) (Figure 4A). Narrow row spacing was effective in reducing weed density by 38% (99% CI = −61% to −0.4%) for broadleaf weeds and by 49% (99% CI = −67% to −22%) for PRE fb POST herbicide application. The reduction in broadleaf weeds is marginally significant (the lower CI is close to 0%); therefore, it cannot be concluded with a high level of confidence that densities of certain weed types (i.e., broadleaves) are more likely to be affected than others (Bradley 2006). Results of the meta-analysis indicate that the benefits of narrow row spacing may likely be achieved with PRE fb POST herbicide application compared with PRE or POST-only or POST fb POST herbicide application, as weed densities may be high due to emergence during the early season (in the case of POST-only, and POST fb POST) or

Table 1. List of 35 published articles included in the meta-analysis, along with information on location, year, weed, crops, agronomic management, and row-spacing treatments included in each study.

Reference	Location	Year	Scientific name of weed	Common name of weed	Family	Weed type[a]	Crop[b]	Tillage[c]	Weed management[d]	Herbicide application[e]	Herbicide application time	Row spacing —cm—
Bailey et al. 2015	Arlington, WI	2013–2014	*Chenopodium album* L. *Solanum ptychanthum* Dunal *Setaria faberi* Herrm. *Polygonum persicaria* L. *Amaranthus powellii* S. Watson *Abutilon theophrasti* Medik. *Setaria pumila* (Poir.) Roem. & Schult.	Common lambsquarters Eastern black nightshade Giant foxtail Ladysthumb smartweed Powell amaranth Velvetleaf Yellow foxtail	Chenopodiaceae Solanaceae Poaceae Polygonaceae Amaranthaceae Malvaceae Poaceae	M	Soy	—	NH	—	—	38
Bowman et al. 1986	Champaign, IL	1981–1983	—	—	—	—	Soy	CT, RT	H	—	—	25
Buehring et al. 2002	Verona, MS	1997–1998	*Senna obtusifolia* (L.) Irwin & Barneby	Sicklepod	Fabaceae	B	Soy	CT	H, NH	S, Seq	PRE, POST, PRE fb POST, POST fb POST	19, 38
Burnside 1979	Lincoln, NE	1973–1975	*Abutilon theophrasti* Medik. *Setaria viridis* (L.) P. Beauv. *Amaranthus tuberculatus* (Moq.) Sauer *Digitaria sanguinalis* (L.) Scop. *Helianthus annuus* L.	Velvetleaf Green foxtail Waterhemp Large crabgrass Common sunflower	Malvaceae Poaceae Amaranthaceae Poaceae Asteraceae	M	Soy	CT	NH	—	—	38
Burnside and Colville 1964	Lincoln, NE	1961–1962	*Amaranthus hybridus* L. *Chenopodium album* L. *Abutilon theophrasti* Medik. *Setaria* spp. *Digitaria* spp. *Panicum dichotomiflorum* Michx. *Eragrostis cilianensis* (All.) Vign. ex Janchen	Smooth pigweed Common lambsquarters Velvetleaf Foxtail Crabgrass Fall panicum Stinkgrass	Amaranthaceae Chenopodiaceae Malvaceae Poaceae Poaceae Poaceae Poaceae	M	Soy	CT, RT	H, NH	S	PRE	25, 51, 102
Carey and Defelice 1991	Columbia and Novelty, MO	1988–1989	*Chenopodium album* L. *Xanthium strumarium* L. *Setaria faberi* Herrm. *Conyza canadensis* (L.) Cronquist	Common lambsquarters Common cocklebur Giant foxtail Horseweed	Chenopodiaceae Asteraceae Poaceae Asteraceae	M	Soy	RT	H	—	—	20
Dalley et al. 2004a	Clarksville and East Lansing, MI	1998–1999	*Echinochloa crus-galli* (L.) P. Beauv. *Chenopodium album* L. *Ambrosia artemisiifolia* L. *Panicum dichotomiflorum* Michx. *Setaria faberi* Herrm. *Setaria viridis* (L.) P. Beauv. *Amaranthus retroflexus* L. *Abutilon theophrasti* Medik. *Setaria pumila* (Poir.) Roem. & Schult.	Barnyardgrass Common lambsquarters Common ragweed Fall panicum Giant foxtail Green foxtail Redroot pigweed Velvetleaf Yellow foxtail	Poaceae Chenopodiaceae Asteraceae Poaceae Poaceae Poaceae Amaranthaceae Malvaceae Poaceae	M B/M B M M M B/M M M	C, Soy	RT	H, NH	S	POST	19, 38
Dalley et al. 2004b	East Lansing, MI	1998–2001	*Echinochloa crus-galli* (L.) P. Beauv. *Chenopodium album* L. *Portulaca oleracea* L. *Ambrosia artemisiifolia* L.	Barnyardgrass Common lambsquarters Common purslane Common ragweed Eastern black	Poaceae Chenopodiaceae Portulacaceae Asteraceae Solanaceae	M	C, Soy	RT	H	S, Seq	POST, POST fb POST	19, 38

Table 1. (*Continued*)

			Solanum ptychanthum Dunal *Panicum dichotomiflorum* Michx. *Setaria faberi* Herrm. *Setaria viridis* (L.) P. Beauv. *Datura stramonium* L. *Amaranthus retroflexus* L. *Abutilon theophrasti* Medik. *Setaria pumila* (Poir.) Roem. & Schult.	nightshade Fall panicum Giant foxtail Green foxtail Jimsonweed Redroot pigweed Velvetleaf Yellow foxtail	Poaceae Poaceae Poaceae Solanaceae Amaranthaceae Malvaceae Poaceae							
Dalley et al. 2006	Clarksville and East Lansing, MI	2001	*Setaria faberi* Herrm. *Setaria viridis* (L.) P. Beauv. *Setaria pumila* (Poir.) Roem. & Schult. *Echinochloa crus-galli* (L.) P. Beauv. *Panicum dichotomiflorum* Michx., *Chenopodium album* L. *Amaranthus retroflexus* L. *Abutilon theophrasti* Medik. *Solanum ptychanthum* Dunal *Datura stramonium* L.	Giant foxtail Green foxtail Yellow foxtail Barnyardgrass Fall panicum Common lambsquarters Redroot pigweed Velvetleaf Eastern black nightshade Jimsonweed	Poaceae Poaceae Poaceae Poaceae Poaceae Chenopodiaceae Amaranthaceae Malvaceae Solanaceae Solanaceae	M	C	CT	H, NH	S	POST	38
Esbenshade et al. 2001a	Manheim, PA	1997–1998	*Sicyos angulatus* L.	Burcucumber	Cucurbitaceae	B	C	RT	H	S	POST	38
Esbenshade et al. 2001b	Manheim, PA	1997–1998	*Sicyos angulatus* L.	Burcucumber	Cucurbitaceae	B	Soy	RT	H	S	POST	38
Harder et al. 2007	Clarksville, East Lansing, and St Charles, MI	2004–2005	*Chenopodium album* L. *Ambrosia artemisiifolia* L. *Setaria faberi* Herrm. *Amaranthus retroflexus* L. *Sinapis arvensis* L. *Barbarea vulgaris* W. T. Aiton	Common lambsquarters Common ragweed Giant foxtail Redroot pigweed Wild mustard Yellow rocket	Chenopodiaceae Asteraceae Poaceae Amaranthaceae Brassicaceae Brassicaceae	M	Soy	—	H, NH	S	POST	19, 38
Hay et al. 2019	Hutchinson, Manhattan, and Ottawa, KS	2017–2018	*Amaranthus palmeri* S. Watson *Amaranthus tuberculatus* (Moq.) Sauer	Palmer amaranth Waterhemp	Amaranthaceae Amaranthaceae	B	Soy	—	NH	—	—	19, 38
Hock et al. 2005	Concord, NE	2002–2003	*Abutilon theophrasti* Medik.	Velvetleaf	Malvaceae	B	Soy	RT	NH	—	—	19
Hock et al. 2006	Concord and Lincoln, NE	2002–2003	*Echinochloa crus-galli* (L.) P. Beauv. *Xanthium strumarium* L. *Helianthus annuus* L. *Panicum dichotomiflorum* Michx. *Setaria faberi* Herrm. *Ambrosia trifida* L. *Amaranthus retroflexus* L. *Amaranthus tuberculatus* (Moq.) Sauer *Abutilon theophrasti* Medik. *Setaria pumila* (Poir.) Roem. & Schult.	Barnyardgrass Common cocklebur Common sunflower Fall panicum Giant foxtail Giant ragweed Redroot pigweed Waterhemp Velvetleaf Yellow foxtail	Poaceae Asteraceae Asteraceae Poaceae Poaceae Asteraceae Amaranthaceae Amaranthaceae Malvaceae Poaceae	G B B G G B B B B G	Soy	CT	NH	—	—	19

(*Continued*)

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Table 1. (*Continued*)

Reference	Location	Year	Scientific name of weed	Common name of weed	Family	Weed type[a]	Crop[b]	Tillage[c]	Weed management[d]	Herbicide application[e]	Herbicide application time	Row spacing —cm—
Johnson and Hoverstad 2002	Waseca, MN	1997–1999	*Setaria faberi* Herrm. *Abutilon theophrasti* Medik. *Chenopodium album* L. *Xanthium strumarium* L. *Ambrosia artemisiifolia* L.	Giant foxtail Velvetleaf Common lambsquarters Common cocklebur Common ragweed	Poaceae Malvaceae Chenopodiaceae Asteraceae Asteraceae	G/M M M M M	C	CT	H, NH	S	PRE, POST	51
Knezevic et al. 2003	Concord and Mead, NE	1999–2001	*Abutilon theophrasti* Medik. *Amaranthus* spp. *Setaria* spp.	Velvetleaf Pigweed Foxtail	Malvaceae Amaranthaceae Poaceae	M	Soy	—	NH	—	—	19, 38
Légère and Schreiber 1989	West Lafayette, IN	1983–1985	*Amaranthus retroflexus* L.	Redroot pigweed	Amaranthaceae	B	Soy	RT	NH	—	—	25
McDonald et al. 2021	Carleton, NE	2018–2019	*Amaranthus palmeri* S. Watson	Palmer amaranth	Amaranthaceae	B	Soy	RT	H, NH	S, Seq	PRE, POST, PRE fb POST, POST fb POST	38
Mickelson and Renner 1997	East Lansing, MI	1994–1995	*Chenopodium album* L. *Abutilon theophrasti* Medik.	Common lambsquarters Velvetleaf	Chenopodiaceae Malvaceae	B	Soy	CT, RT	H	S, Seq	POST, POST fb POST	19
Moomaw and Martin 1984	Madison County, NE	1978–1980	*Setaria viridis* (L.) P. Beauv. *Digitaria sanguinalis* (L.) Scop.	Green foxtail Large crabgrass	Poaceae	G	C	—	H, NH	S, Seq	PRE, Layby, PRE fb Layby	91
Mulugeta and Boerboom 2000	Arlington, WI	1996–1997	*Chenopodium album* L. *Setaria faberi* Herrm.	Common lambsquarters Giant foxtail	Chenopodiaceae Poaceae	M	Soy	RT	H, NH	S	POST	18
Nelson and Renner 1998	Clarksville and East Lansing, MI	1996	*Chenopodium album* L. *Ambrosia artemisiifolia* L. *Setaria faberi* Herrm. *Amaranthus retroflexus* L. *Abutilon theophrasti* Medik.	Common lambsquarters Common ragweed Giant foxtail Redroot pigweed Velvetleaf	Chenopodiaceae Asteraceae Poaceae Amaranthaceae Malvaceae	B/M B/M M B/M M	Soy	CT	H, NH	S	POST	19
Nelson and Renner 1999	East Lansing, MI	1996–1997	*Chenopodium album* L. *Ambrosia artemisiifolia* L. *Solanum ptychanthum* Dunal *Setaria faberi* Herrm. *Amaranthus retroflexus* L. *Abutilon theophrasti* Medik.	Common lambsquarters Common ragweed Eastern black nightshade Giant foxtail Redroot pigweed Velvetleaf	Chenopodiaceae Asteraceae Solanaceae Poaceae Amaranthaceae Malvaceae	B/M B/M B/M G/M B/M B/M	Soy	CT, RT	H, NH	S, Seq	POST, PRE fb POST, POST fb POST	19
Nice et al. 2001	Verona, MS	1997–1998	*Senna obtusifolia* (L.) Irwin & Barneby	Sicklepod	Fabaceae	B	Soy	CT	H, NH	S, Seq	PRE, POST, PRE fb POST, POST fb POST	19,38
Nordby and Hartzler 2004	Ames, IA	2001–2002	*Amaranthus tuberculatus* (Moq.) Sauer	Waterhemp	Amaranthaceae	B	C	RT	NH	—	—	38
Norris et al. 2002	Starkville and Stoneville, MI	1998–1999	*Echinochloa crus-galli* (L.) P. Beauv. *Sesbania herbacea* (Mill.) McVaugh *Digitaria sanguinalis* (L.) Scop. *Ipomoea lacunosa* L. *Senna obtusifolia* (L.) Irwin & Barneby	Barnyardgrass Hemp sesbania Large crabgrass Pitted morningglory Sicklepod	Poaceae Fabaceae Poaceae Convolvulaceae Fabaceae	G/M B/M G/M B/M B/M	Soy	CT	H, NH	S, Seq	PRE, POST, PRE fb POST, POST fb POST	38
Rich and Renner 2007	Clarksville and East Lansing, MI	2001–2002	*Solanum ptychanthum* Dunal	Eastern black nightshade	Solanaceae	B	Soy	CT	H	S, Seq	POST, PRE fb POST	19
Schmidt and Johnson 2004	Columbia, MO	2000–2001	*Xanthium strumarium* L. *Ambrosia artemisiifolia* L. *Setaria faberi* Herrm. *Ipomoea hederacea* Jacq.	Common cocklebur Common ragweed Giant foxtail Ivyleaf morningglory	Asteraceae Asteraceae Poaceae Convolvulaceae	B B G B	Soy	RT	H, NH	S	POST	38

Table 1. (*Continued*)

Schultz et al. 2015	Randolph County, MO	2012–2013	*Amaranthus tuberculatus* (Moq.) Sauer	Waterhemp	Amaranthaceae	B	Soy	CT	H	Seq	—	19, 38
Steckel and Sprague 2004	Urbana, IL	200–2002	*Amaranthus tuberculatus* (Moq.) Sauer	Waterhemp	Amaranthaceae	B	Soy	RT	NH	—	—	19
Tharp and Kells 2001	East Lansing, MI	1998–1999	*Chenopodium album* L.	Common lambsquarters	Chenopodiaceae	B	C	CT	H	S	POST	38,56
VanGessel et al. 2003	Georgetown and Port Penn, DE	1997–1998	*Solanum carolinense* L. *Cirsium arvense* (L.) Scop.	Horsenettle Canada thistle	Solanaceae Asteraceae	B	Soy	RT	H	Seq	PRE fb POST	19, 25, 38, 51
Wax and Pendleton 1968	Urbana, IL	1965–1966	*Setaria faberi* Herrm. *Digitaria* spp. *Amaranthus hybridus* L. *Sida spinosa* L. *Abutilon theophrasti* Medik.	Giant foxtail Crabgrass Smooth pigweed Prickly sida Velvetleaf	Poaceae Poaceae Amaranthaceae Malvaceae Malvaceae	M	Soy	CT, RT	H	S	PRE	25, 51, 102
Young et al. 2001	Belleville, Dekalb, and Urbana, IL	1996–1998	*Amaranthus tuberculatus* (Moq.) Sauer *Setaria faberi* Herrm. *Abutilon theophrasti* Medik.	Waterhemp Giant foxtail Velvetleaf	Amaranthaceae Poaceae Malvaceae	B/M G/M B/M	Soy	CT, RT	H, NH	S, Seq	POST, PRE fb POST, POST fb POST	19, 38

[a]B, broadleaf weed; G, grass weed; M, mixed weed species.
[b]C, corn; Soy, soybean.
[c]CT, conventional tillage; RT, reduced tillage.
[d]H, herbicide; NH, no-herbicide (untreated/weedy).
[e]S, single application; Seq, Sequential application.

resurgence (in the case of PRE-only) during the late season. For example, McDonald et al. (2021) reported 3 to 32 versus 123 to 497 plants m^{-2} of *A. palmeri* with PRE fb POST versus POST-only herbicide programs in a soybean row-spacing study conducted in Nebraska. However, the weed density data set had only one study each for PRE (Johnson and Hoverstad 2002) and POST fb POST herbicide application (McDonald et al. 2021); therefore, no definitive conclusion could be drawn.

Effects of Narrow Row Spacing on Weed Biomass

Averaged across 283 pair-wise comparisons from 20 studies, narrow row spacing (<76 cm) reduced overall weed biomass by 55% (Figure 3; 95% CI = −68% to −36%). Meta-regression further suggests that individual effect sizes of weed biomass had a very low degree of positive correlation ($R = 0.13$; $P = 0.024$) with row spacing (Figure 5B). Similarly, Hay et al. (2019) observed a weak positive correlation between weed biomass and soybean row spacing in Kansas. The researchers combined 118 observations from 6 site-years and found that pigweed (*Amaranthus* spp.) biomass at 8 wk after planting was reduced by 23% when row spacing was decreased from 76 to 38 cm and by 15% when row spacing was further decreased from 38 to 19 cm. Most of the individual observations for soybean had narrow row spacing ≤ 51 cm ($n = 224$ out of 260), and 82% of these observations ($n = 184$ out of 224) were concentrated below the zero-effect size (i.e., black dashed line; Figure 5B). Out of these 184 observations, about one-fifth of the observations ($n = 32$) had high negative effect sizes of < −2.3, because reported biomass was negligible (0 g; replaced with 0.1 g to calculate effect sizes) for thenarrow row spacing treatments. As a result, an overall estimate of 71% (99% CI = −85% to −44%) suppression in weed biomass due to narrow row spacing was observed in soybean (Figure 4B). This is likely because narrow row spacing closes the canopy earlier and provides greater competitiveness against weeds than wide row spacing. For example, researchers observed that soybean with 19-cm row spacing closed its canopy 20 to 45 d earlier than soybean with 76-cm row spacing (20 d [Carey and Defelice 1991; Hock et al. 2006]; 35 d [Nelson and Renner 1998; Rich and Renner 2007]; 45 d [Mickelson and Renner 1997]). Moderator analysis revealed that narrow row spacing suppressed weed biomass in all cases, except for corn, conventional tillage, grass weed species, and untreated/weedy plots (Figure 4B). The weed biomass was likely not reduced in corn because, unlike in soybean, any significant season-long increase in light interception was essentially not observed with narrow compared with wider row spacing in corn (Bradley 2006). Tharp and Kells (2001) reported that corn row spacing narrower than 76 cm intercepted a greater quantity of light (not more than 10%) than 76-cm row spacing in just the early season, with no differences later in the season. Likewise, other researchers reported that narrow row spacing did not increase interception efficiency (35 vs. 66 cm; Flénet et al. 1996) or maximum interception of photosynthetic active radiation (38 vs. 76 cm; Ottman and Welch 1989; Westgate et al. 1997) in corn. Moreover, any increase in light interception or crop competitiveness with narrow row spacing in corn might not translate into early-season reduction in weed density or biomass (Johnson et al. 1998; Johnson and Hoverstad 2002).

Weed biomass was suppressed by 64% (99% CI = −81% to −33%) for reduced tillage, 56% (99% CI = −78% to −11%) for broadleaf weeds, and 61% (99% CI = −80% to −26%) for mixed

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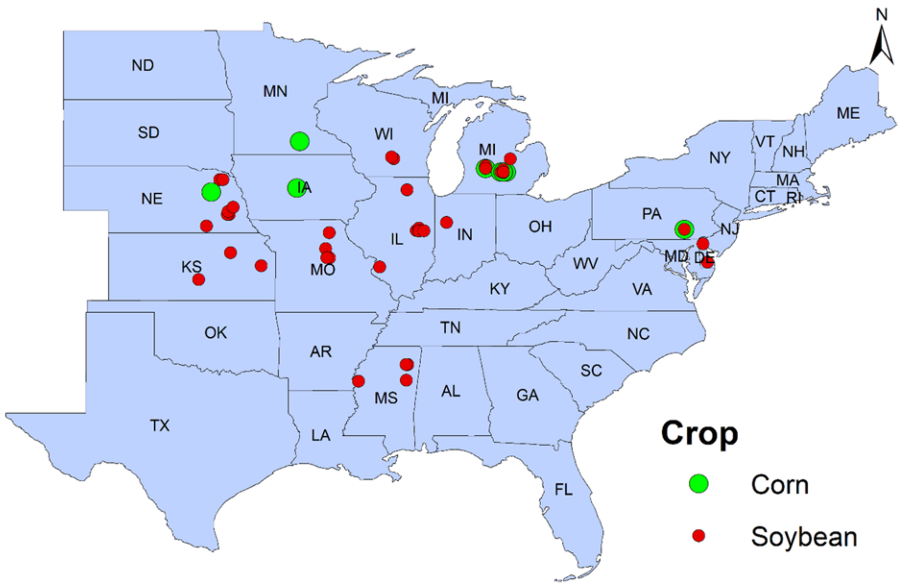

Figure 2. A map of the states in the midwestern and eastern United States showing experimental sites for the 35 corn and soybean narrow row spacing studies included in the meta-analysis.

weeds (Figure 4B). The effect of reduced tillage is possibly due to more observations with a high negative effect size of < −3.0 compared with conventional tillage ($n = 35$ vs. 2 for conventional tillage). For most of these observations, biomass in narrow row spacing was almost zero and was compared with higher biomass (3 to 919 kg ha^{-1}) from 76-cm row spacing. The reason for negligible biomass was that it was initially suppressed by glyphosate applied POST (Dalley et al. 2004b; Mulugeta and Boerboom 2000) or by PRE application of 3-amino-2,5-dichlorobenzoic acid with or without in-season rotary till hoe treatments (Burnside and Colville 1964), and thereafter, weeds may not have emerged in narrow row spacing due to early canopy shading, unlike in 76 cm rows with wide open spaces to let weeds emerge and thrive. Similarly, a significant effect for broadleaf and mixed weed species was observed, but not for grass weed species, as more than one-third of the observations ($n = 9$ out of 23) for grasses had a positive effect size (0.12 to 1.04; Hock et al. 2006; Johnson and Hoverstad 2002; Schmidt and Johnson 2004). However, this data set for grasses was relatively small ($n = 23$ compared with 68 for broadleaf and 192 for mixed weed species) to firmly conclude that the biomass of grass weed species is more likely to be affected than other weed types. When herbicides were used, weed biomass suppression was 69% (99% CI = −81% to −48%), with slightly lower suppression of 67% (99% CI = −84% to −33%) with single use compared with 79% (99% CI = −87% to −68%) with sequential application of herbicides. This was expected, as a follow-up application of herbicide helps control weed escapes from the first application and late-emerging weeds (Norris et al. 2002; Young et al. 2001). Among herbicide application timings, PRE (mean = −46%, 99% CI = −52% to −39%) had approximately half the suppression of POST (mean = −79%, 99% CI = −88% to −64%), PRE fb POST (mean = −83%, 99% CI = −86% to −78%), and POST fb POST (mean = −84%, 99% CI = −84% to −84%) herbicide programs. Therefore, results indicate that cultural practices such as narrow row spacing, and reduced tillage should be combined with chemical options such as sequential (PRE fb POST) herbicide applications to effectively suppress weeds in production fields.

Effects of Narrow Row Spacing on Weed Control

Averaged across 792 pair-wise comparisons from 13 studies, overall weed control improved by 32% (95% CI = 1 to 74%) with crop row spacing narrower than 76 cm (Figure 3). Almost all the observations for weed control were recorded in soybean ($n = 791/792$) and reported a 32% (99% CI = −9 to −91%) increase in weed control with no significant difference (Figure 4C). Among other moderate variables, the improvement in weed control was observed with no-herbicide plots (mean effect size of 3.3), a single application of herbicide (mean = 11%, 99% CI = 3 to 19%), and POST-only (mean = 14%, 99% CI = 1 to 29%) herbicide application. Only 15% of the observations ($n = 63$) of the extensive POST data set ($n = 428$) had a negative effect size (−0.01 to −0.55), which led to the overall effect of 14% weed control with smaller CIs (1% to 29%). Weed control and row spacing had negligible negative correlation (R = −0.023) with no significance (Figure 5C; P = 0.52). Because all of the narrow row spacing observations belonged to ≤51-cm row spacing, this implies that weed control might be almost similar with 19-, 25-, or 38-cm row spacings. For example, Young et al. (2001) observed that 19- versus 38-cm soybean row spacing had no differences in control of *S. faberi*, *A. tuberculatus*, and *A. theophrasti* in 6 out of 8 site-years, 4 out of 5 site-years, and 5 out of 8 site-years, respectively.

Effects of Narrow Row Spacing on Weed Seed Production

Averaged across 36 pair-wise comparisons from five studies, weed seed production was reduced by 45% (95% CI = −66% to −9%; Figure 3). The effects of narrow row spacing were only significant for plots with herbicide use (mean = −61%, 99% CI = −81% to −18%) of single (mean = −36%, 99% CI = −53% to −14%) and sequential (mean = −49%, 99% CI = −62% to −31%) applications and POST fb POST (mean = −61%, 99% CI = −78% to −29%) herbicide application timing (Figure 4D). Nice et al. (2001) observed that a sequential POST glyphosate program was quite effective in reducing *S. obtusifolia* seed production in 19- and 38-cm compared with 76-cm row spacing (50 to 150 seeds m^{-2} vs. 260 seeds m^{-2}). Weed seed

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Table 2. List of the states in the United States, crops, and broadleaf and grass weeds, along with specific references from the 35 articles included in the meta-analysis.

State	References
Delaware	VanGessel et al. 2003
Illinois	Bowman et al. 1986; Steckel and Sprague 2004; Wax and Pendleton 1968; Young et al. 2001
Indiana	Légère and Schreiber 1989
Iowa	Nordby and Hartzler 2004
Kansas	Hay et al. 2019
Michigan	Dalley et al. 2004a, 2004b, 2006; Harder et al. 2007; Mickelson and Renner 1997; Nelson and Renner 1998, 1999; Rich and Renner 2007; Tharp and Kells 2001
Minnesota	Johnson and Hoverstad 2002
Mississippi	Buehring et al. 2002; Nice et al. 2001; Norris et al. 2002
Missouri	Carey and Defelice 1991; Schmidt and Johnson 2004; Schultz et al. 2015
Nebraska	Burnside 1979; Burnside and Colville 1964; Hock et al. 2005, 2006; Knezevic et al. 2003; McDonald et al. 2021; Moomaw and Martin 1984
Pennsylvania	Esbenshade et al. 2001a, 2001b
Wisconsin	Bailey et al. 2015; Mulugeta and Boerboom 2000
Crop	
Corn	Dalley et al. 2006; Esbenshade et al. 2001a; Johnson and Hoverstad 2002; Moomaw and Martin 1984; Nordby and Hartzler 2004; Tharp and Kells 2001
Corn and soybean	Dalley et al. 2004a, 2004b
Soybean	Remaining 27 references provided in Table 1
Broadleaf weeds	
Burcucumber (*Sicyos angulatus* L.)	Esbenshade et al. 2001a, 2001b
Canada thistle [*Cirsium arvense* (L.) Scop.]	VanGessel et al. 2003
Common cocklebur (*Xanthium strumarium* L.)	Hock et al. 2006; Schmidt and Johnson 2004
Common lambsquarters (*Chenopodium album* L.)	Mickelson and Renner 1997; Nelson and Renner 1998, 1999; Tharp and Kells 2001
Common ragweed (*Ambrosia artemisiifolia* L.)	Nelson and Renner 1998, 1999; Schmidt and Johnson 2004
Common sunflower (*Helianthus annuus* L.)	Hock et al. 2006
Eastern black nightshade (*Solanum ptycanthum* Dunal)	Nelson and Renner 1999; Rich and Renner 2007
Giant ragweed (*Ambrosia trifida* L.)	Hock et al. 2006
Hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh]	Norris et al. 2002
Horsenettle (*Solanum carolinense* L.)	VanGessel et al. 2003
Ivyleaf morningglory (*Ipomoea hederacea* Jacq.)	Schmidt and Johnson 2004
Palmer amaranth (*Amaranthus palmeri* Watson)	Hay et al. 2019; McDonald et al. 2021
Pitted morningglory (*Ipomoea coccinea* L.)	Norris et al. 2002
Redroot pigweed (*Amaranthus retroflexus* L.)	Hock et al. 2006; Légère and Schreiber 1989; Nelson and Renner 1998, 1999
Sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby]	Buehring et al. 2002; Nice et al. 2001; Norris et al. 2002
Waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]	Hay et al. 2019; Hock et al. 2006; Nordby and Hartzler 2004; Schultz et al. 2015; Steckel and Sprague 2004; Young et al. 2001
Velvetleaf (*Abutilon theophrasti* Medik.)	Hock et al. 2005, 2006; Mickelson and Renner 1997; Nelson and Renner 1999; Young et al. 2001
Grass weeds	
Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]	Hock et al. 2006; Norris et al. 2002
Fall panicum (*Panicum dichotomiflorum* Michx.)	Hock et al. 2006
Giant foxtail (*Setaria faberi* Herrm.)	Hock et al. 2006; Johnson and Hoverstad 2002; Nelson and Renner 1999; Schmidt and Johnson 2004; Young et al. 2001
Large crabgrass [*Digitaria sanguinalis* (L.) Scop.]	Norris et al. 2002
Yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.]	Hock et al. 2006

production had a moderate degree of positive association (R = 0.46) of high significance (P < 0.001) with row spacing (Figure 5D). Weed seed production decreased with a decrease in row spacing, although a significant decrease was only reported with 19-cm row spacing (95% CIs shaded in Figure 5D, as the gray area did not overlap with zero effect size or the black dashed line). The findings from Steckel and Sprague (2004) correspond with this observation: in their study, seed production of *A. tuberculatus*, which emerged at the V2-V3 soybean stage, decreased from 20,000 to 14,000 seeds plant^{-1} in 19-cm compared with 76-cm row spacing, and likewise decreased from 4,300 to 500 seeds plant^{-1} for those that emerged at the V4-V5 growth stage of soybean.

Effects of Narrow Row Spacing on Crop Yield

Averaged across 478 pair-wise comparisons from 20 studies, overall crop yield increased by 11% (95% CI = 6% to 16%) with row spacing narrower than 76 cm (Figure 3). However, this increase was only evident in soybean (mean = 12%, 99% CI = 6% to 18%), not in corn (Figure 5; mean = 4%, 99% CI = −8% to 17%). This is likely because the number of studies that evaluated the effect of narrow row spacing on corn yield was small ($n = 4$), and the results were mixed; Esbenshade et al. (2001a) and Tharp and Kells (2001) reported no effect of narrow row spacing on corn yield, Johnson and Hoverstad (2002) reported a mostly positive effect, and Dalley

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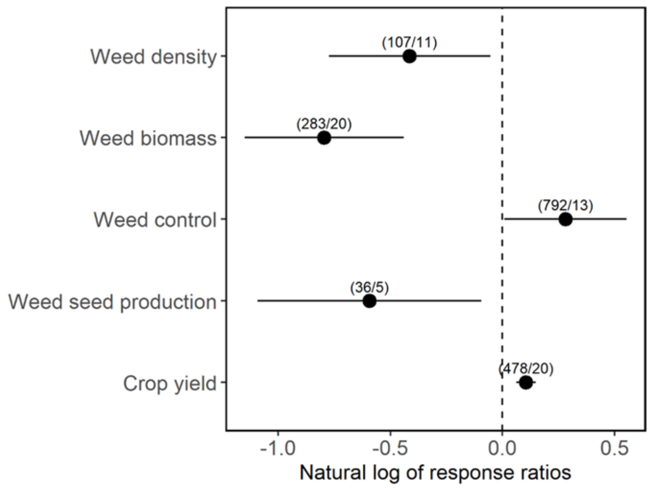

Figure 3. The overall effect of narrow row spacing (<76 cm) on weed density, weed biomass, weed control, weed seed production, and crop yield. The vertical black dashed line indicates zero effect. The black dots represent mean effect sizes (log of response ratios [$\overline{\ln(RR)}$]), and the black lines represent their respective 95% confidence intervals (CIs). The numbers in parentheses indicate the number of observations followed by the number of studies for each effect size. The effect sizes were considered significantly different when their 95% CIs did not overlap or contain zero.

et al. (2004a) reported both a negative and a positive effect. The mixed response of corn yield to narrow row spacing was attributed to variable levels of weed suppression, environmental conditions, and other factors, such as the timing of herbicide application (Dalley et al. 2004a; Esbenshade et al. 2001a; Johnson and Hoverstad 2002; Tharp and Kells 2001). In future, more studies evaluating narrow row spacing effects in corn systems are required.

In soybean, about one-fourth (21%) of the observations ($n = 96$ out of 458) noted lower yield with narrow row spacing; however, 59% of these observations ($n = 57$ out of 96) came from a single study, in which the authors reported poor crop establishment in 19-cm row spacing in at least 1 site-year (Young et al. 2001). Similarly, Norris et al. (2002) observed no yield advantage of narrow row spacing due to dry weather conditions or lower population in narrow row spacing and accounted for 15 observations with zero and negative yield effects. However, soybean yield increased in narrow row spacing due to positive effect size in 77% of total observations ($n = 354$ out of 458). The positive effect of narrow row spacing on soybean yield is usually attributed to the more equidistant distribution of plants, improved crop competitiveness, decreased intraspecific competition for resources such as light, and early canopy closure (Bradley 2006; Harder et al. 2007; Norris et al. 2002). Furthermore, individual effect sizes for crop yields and row spacing had a low degree of negative association ($R = -0.26$) with high significance ($P < 0.001$; Figure 5E). As crop row spacing became wider from 19 cm to 76 cm (control), or beyond this to 102 cm, the general trend of progressive decrease in crop yield was observed. This suggests that crops in narrow row spacing are more competitive with weeds and have higher resource use efficiency than those in wider row spacing (Knezevic et al. 2003).

Crop yield increased by 8% (99% CI = 0.2% to 16%) due to narrow row spacing under conventional tillage compared with 11% (99% CI = 3% to 19%) under reduced tillage (Figure 6). Further, crop yield increased due to narrow row spacing when weeds were either partially/fully controlled via herbicide application (mean = 9%, 99% CI = 3% to 15%) or not controlled, as in the case of untreated/weedy plots (mean = 27%, 99% CI = 17% to 38%). However, there was no increase in crop yield in weed-free plots (mean = 6%, 99% CI = −4% to 17%). These results suggest that the positive effect of narrow row spacing on crop yield is partially related to its weed-suppression effects, among other factors. Interestingly, crop yield was increased with a single application of herbicide (mean = 9%, 99% CI = 3% to 17%); for example, a crop yield increase of 19% (99% CI = 5% to 34%) was observed with PRE herbicide and 8% (99% CI = 1% to 16%) with POST herbicide.

Publication Bias and Sensitivity Analysis

The distribution of individual effect sizes for weed density, weed biomass, weed control, weed seed production, and crop yield is plotted as a density plot in Figure 7. The individual effect sizes for weed control and crop yield were distributed in a narrow range compared with other response variables and had peaks indicating a slightly positive effect of narrow row spacing (<76 cm). In contrast, weed density, weed biomass, and weed seed production had comparatively wide distributions, with peaks indicating a slightly negative effect. The response variables had a fairly symmetrical distribution with an inverted funnel shape, which is indicative of no publication bias (Light et al. 1984; Sterne and Harbord 2004).

Sensitivity analysis did not find any influential study for the weed density, weed biomass, weed seed production, and crop yield data set (Figure 8). One study was found to be influential for weed control; with the exclusion of Buehring et al. (2002), weed control decreased by more than half from 32% (95% CI = 1 to 74%) to 15% (95% CI = 6% to 24%). This occurred because 22 individual observations from this study reported 3% to 52% weed control ratings for narrow row-spacing treatments of 19 and 38 cm compared with a 0% control (imputed control of 0.1%) for the untreated control of standard 76-cm row spacing. This led to seemingly high effect sizes of 3.4 to 6.3, which more than doubled (15% vs. 32%) the overall effect size for weed control. Overall, the results of this meta-analysis are robust, as no other single study had any significant influence on the mean effect sizes.

Limitations and Factors to Consider for Interpreting Results

- Most of the published articles used in this meta-analysis did not report standard SDs or SEs, which prevents the calculation of sampling variance of log response ratios ($\overline{\ln(RR)}$) (Nakagawa et al. 2023). Excluding these studies from the data set or conducting the unweighted analysis may result in biased estimates of overall effect sizes (Kambach et al. 2020); therefore, we encourage researchers to adhere to data standards and reporting principles by reporting SDs or SEs and sampling sizes in future studies.
- We confined "search criteria" to the discipline of weed science. This may have led to the exclusion of studies evaluating the effect of narrow row spacing on other agronomic parameters while reporting crop yield (e.g., Bernhard and Below 2020; Bowers et al. 2000; Cox and Cherney 2011; De Bruin and Pedersen 2008; Shapiro and Wortmann 2006). The number of studies pertaining to corn yield (only four: Dalley et al. 2004a; Esbenshade et al. 2001a; Johnson and Hoverstad 2002; Tharp and Kells 2001) included in the meta-analysis was not large enough to draw robust conclusions about the effect of row spacing on corn yield; therefore, readers must cautiously interpret crop yield results from this meta-analysis, as it was limited to extracting

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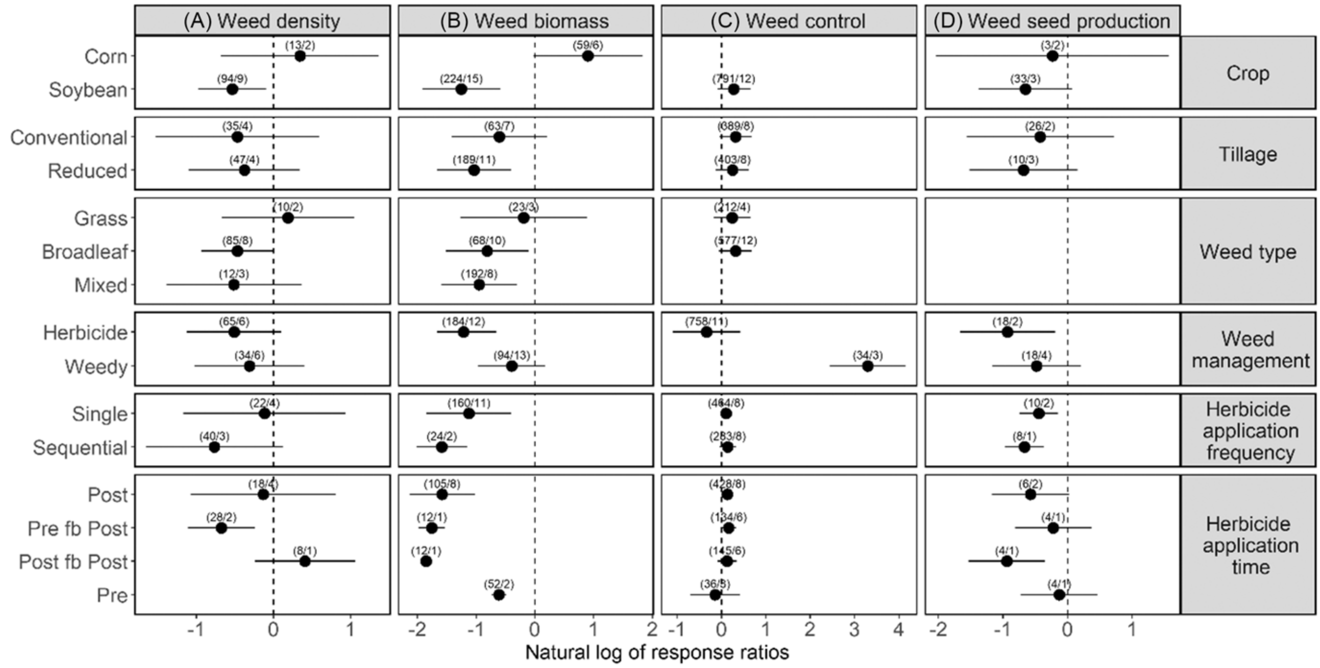

Figure 4. The effect of narrow row spacing (<76 cm) on (A) weed density, (B) weed biomass, (C) weed control, and (D) weed seed production as explained by the subgroups of crop, tillage, weed type, weed management method, herbicide application frequency, and time. The vertical black dashed line indicates zero effect. The black dots represent mean effect sizes (log of response ratios [$\overline{\ln(RR)}$]) for each subgroup, and the black lines represent their respective 99% confidence intervals (CIs). The numbers in parentheses indicate the number of observations followed by the number of studies for each effect size. The effect sizes were considered significantly different when their 99% CIs did not overlap or contain zero.

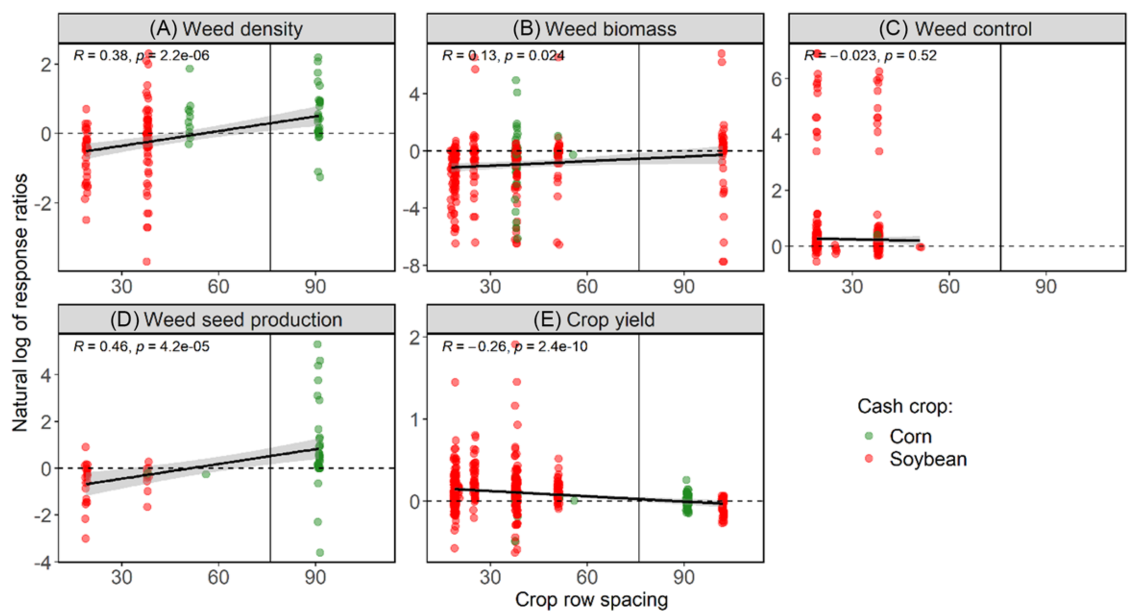

Figure 5. The individual effect sizes (natural log of response ratios [$\overline{\ln(RR)}$]) of (A) weed density, (B) weed biomass, (C) weed control, (D) weed seed production, and (E) crop yield as a function of crop row spacing. The green and red dots represent individual effect sizes for corn and soybean, respectively. The horizontal black dashed line represents zero effect, while the vertical black line represents 76-cm row spacing (control). The black bold line shows the relationship between individual effect sizes and crop row spacing, which is given as R (Pearson's correlation) with a P-value. The gray-shaded area represents 95% confidence intervals (CIs) of the linear relationship.

data from the 35 studies that fit search criteria. The studies that reported crop yield but did not fit the search criteria can be included for a more robust synthesis of the effect of narrow row spacing on corn and soybean yield.

- Seeding rate or planting population is a critical factor that determines crop yield (Cox and Cherney 2011). In this meta-analysis, we were unable to account for seeding rate and plant population, because both were different across narrow row spacing (<76 cm) and 76-cm row-spacing treatments (Burnside and Colville 1964; Burnside 1979; Carey and Defelice 1991; Mickelson and Renner 1997; Mulugeta and Boerboom 2000; Nelson and Renner 1998, 99; Rich and Renner 2007; Wax

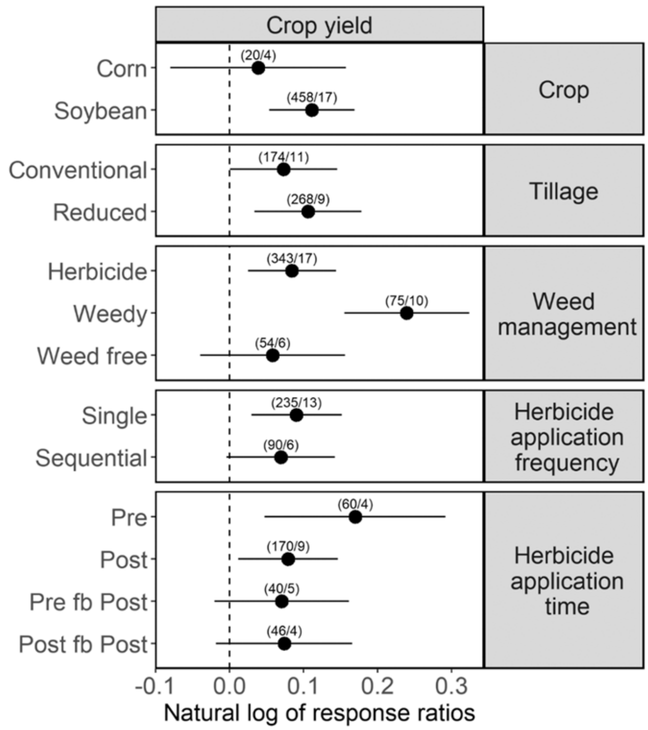

Figure 6. The effect of narrow row spacing (<76 cm) on crop yield as explained by subgroups of the crop, tillage, weed type, weed management method, herbicide application frequency, and time. The vertical black dashed line indicates zero effect. The black dots represent mean effect sizes (log of response ratios [ln(*RR*)]) for each subgroup, and the black lines represent their respective 99% confidence intervals (CIs). The numbers in parentheses indicate the number of observations followed by the number of studies for each effect size. The effect sizes were considered significantly different when their 99% CIs did not overlap or contain zero.

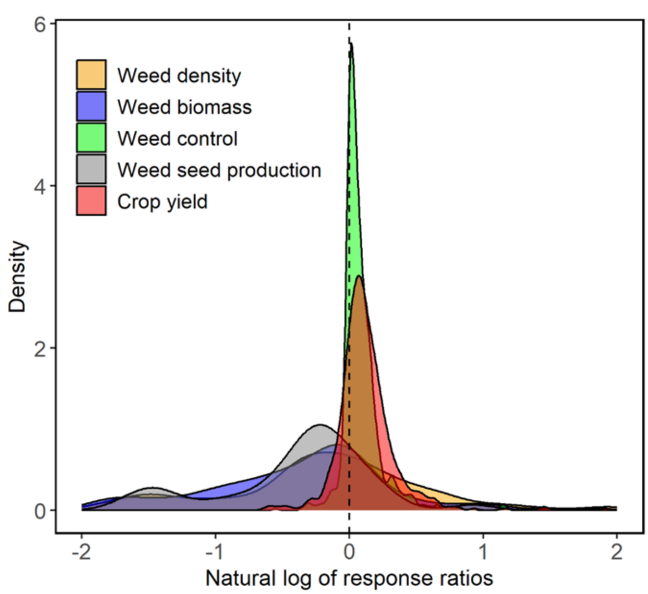

Figure 7. Density plots show the distribution of individual effect sizes (log of response ratios [ln(RR)]) of weed density, biomass, control, weed seed production, and crop yield.

and Pendleton 1968; Young et al. 2001) or means of some response variables were averaged for multiple seeding rate/plant population treatments (Harder et al. 2007; Schultz et al. 2015; Tharp and Kells 2001). This prevented making valid comparisons. Seeding rate or plant population at specific row spacing makes a difference, as yield in wide row spacing may increase with a higher plant population (Carey and Defelice 1991; Mickelson and Renner 1997). For example, Harder et al. (2007) reported that soybean yield of 76-cm row spacing (1,280 kg ha^{-1}) was less (400 kg ha^{-1}) than soybean yield of 19-cm row spacing (1,680 kg ha^{-1}) at a lower plant population of 185,000 to 198,000 plants ha^{-1}; however, increasing the plant population to 445,000 plants ha^{-1} in 76-cm row spacing did not produce a different yield (1,670 kg ha^{-1}) than 19-cm row spacing at a lower plant population. Additionally, increasing the plant populations of 19- and 38-cm row spacing improved crop competitiveness and yield (Harder et al. 2007). Moreover, plant population could influence the time to canopy closure, which further affects weed suppression. Harder et al. (2007) noticed that canopy closure was delayed by 1 wk in 76-cm soybean row spacing at lower densities of 124,000 to 309,000 plants ha^{-1} (12 wk after planting) compared with the higher density of 445,000 plants ha^{-1} (11 wk after planting). Therefore, evaluating the interaction of plant population with row spacing as a potential covariate can help in drawing more accurate conclusions, given that the plant population is the same across standard and narrow row-spacing treatments.

- Some studies have reported the role of narrow row spacing in reducing herbicide use (Mulugeta and Boerboom 2000; Nelson and Renner 1999; Norris et al. 2002). However, dense canopies of narrow row spacing may intercept herbicide if application is delayed, and therefore reduce the amount reaching weeds below the canopy, leading to lower weed control (Nelson and Renner 1998). In either case, herbicides should be applied at recommended rates to avoid selection pressure for the evolution of herbicide-resistant weeds (Norsworthy et al. 2012). Further, factors such as cultivar selection (Burnside 1979), geographic location (Lee 2006), economic profits (i.e., weighing equipment and production costs against potential advantages) (De Bruin and Pedersen 2008), lodging concerns (Cooper 1971; Weber et al. 1966), the occurrence of *Sclerotinia* stem rot (Grau and Radke 1984) and other pathogens (Bowman et al. 1986), planting time (Oplinger and Philbrook 1992), and the relative time of weed emergence (Esbenshade et al. 2001a; Hock et al. 2006) could play a role in the adoption of narrow row spacing in corn and soybean production fields. Therefore, although narrow row spacing could be used among the portfolio of strategies available for weed management, its acceptance, adoption, and success will depend on the complex interactions of the aforementioned factors along with weed control and yield benefits.

Practical Implications

This is the first meta-analysis to quantify the effect of narrow row spacing (<76 cm) on weed density, weed biomass, weed control, weed seed production, and yield of corn and soybean in the United States. A synthesis of relevant studies suggests that narrow row spacing could reduce weed density by 34%, weed biomass by 55%, and weed seed production by 45% and could increase weed control by 32% and crop yield by 11% compared with 76-cm row spacing; however, weed suppression and yield improvement were discovered

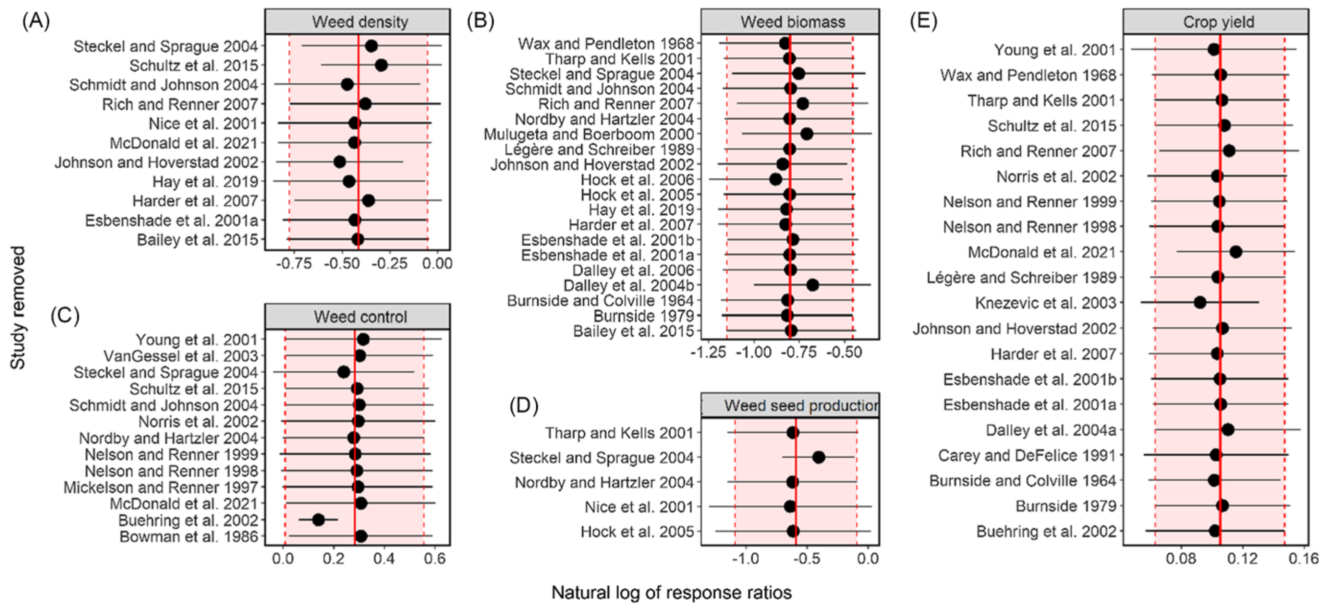

Figure 8. Sensitivity analysis showing the variation in overall effect sizes (log of response ratios [ln(RR)]) (mean ± 95% confidence intervals [CIs]) of narrow row spacing effects on (A) weed density, (B) weed biomass, (C) weed control, (D) weed seed production, and (E) crop yield when any specific study was excluded from the analysis. The vertical red solid and dashed lines represent the mean ± 95% CIs, respectively, of overall effect sizes with all the studies included in the analysis.

in soybean, not in corn. Narrow row spacing in soybean reduced weed density by 42% and weed biomass by 71% and improved crop yield by 12%. Results of this study substantiate literature that narrow row spacing can suppress (late-season) weeds mostly in soybean and rarely in corn (Bradley 2006). Moreover, narrow row spacing may delay the critical time for weed removal in soybean; for example, the critical time for weed removal occurred at the V1 soybean growth stage in 76-cm row spacing and at the V2 and V3 stages for 38- and 19-cm row spacing, respectively (Knezevic et al. 2003). This indicates that weed management programs are required earlier in wide row spacing (76 cm) compared with narrow row spacing. The potential advantages of narrow row spacing, such as higher weed suppression due to early canopy closure and improved crop yield, may not be achieved if soybean growth and yield potential are limited by moisture or other critical factors (Harder et al. 2007). Overall, results suggest that narrow row spacing can potentially be used as an integrated weed management tool in combination with herbicides in soybean for the management of herbicide-resistant weeds.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2023.50

Data Availability Statement. The raw data will be available upon request from the corresponding author.

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