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Implications of cover crop management decisions on *Amaranthus* species density and biomass in temperate cropping systems: a meta-analysis

Review

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Abstract

Weed-suppression benefits of cover crops (CCs) have long been recognized; however, the specific ability of CCs to suppress highly epidemic *Amaranthus* spp. (Palmer amaranth (*Amaranthus palmeri* S. Watson), redroot pigweed (*Amaranthus retroflexus* L.), smooth pigweed (*Amaranthus hybridus* L.), and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer]) has not been widely discussed. The objective of this meta-analysis was to evaluate the implications of CC management decisions (CC type, planting and termination methods, residue fate after termination, and in-season weed management plan) on *Amaranthus* spp. weed density (ASWD) and *Amaranthus* spp. weed biomass (ASWB) compared with no CC (NCC) in temperate regions, including the United States and Canada. We found 41 studies conducted across the United States and Canada and extracted 595 paired observations. The results indicate that CCs reduced the ASWD by 58% in the early season (0 to 4 wk after crop planting [WAP]), by 48% in the midseason (5 to 8 WAP), and by 44% in the late season (>8 WAP). Similarly, CCs reduced ASWB by 59%, 55%, and 37% in the early, mid-, and late season, respectively. Meta-regression analysis showed CCs terminated within 2.5 wk of crop planting reduced ASWD by ≥50%. CC biomass required to reduce ASWD and ASWB by 50% was 4,079 kg ha^{-1} for ASWD and 5,352 kg ha^{-1} for ASWB. Among CC types, grasses and mixtures reduced ASWD by 60% and 77% in early season, 53% and 59% in midseason, and 44% and 47% in late season. Legume CCs were effective only during the early season (47% ASWD reduction), while brassicas did not affect ASWD. CC residues remaining on the soil surface were more effective for reducing ASWD than incorporation. CCs did not affect ASWD or ASWB compared with NCC when herbicides were used for in-season weed management. In general, CCs were found to reduce ASWD and ASWB and therefore can be used as an effective tool for integrated management of *Amaranthus* spp.

Introduction

Amaranthus is a genetically diverse plant genus with about 75 species (Ward et al. 2013) distributed across 6 out of the 7 continents (Assad et al. 2017). Some of the *Amaranthus* species are highly invasive and considered economically important weeds (Sarangi et al. 2021), commonly called pigweeds. Four *Amaranthus* spp. weeds (ASW), viz. Palmer amaranth (*Amaranthus palmeri* S. Watson), redroot pigweed (*Amaranthus retroflexus* L.), smooth pigweed (*Amaranthus hybridus* L.), and waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], are widely prevalent in the U.S. crop (hereafter “crop” refers to cash crop unless specified) production systems (Horak and Loughin 2000; Sarangi et al. 2021). In surveys conducted by the Weed Science Society of America in 2020 and 2022, *A. palmeri* was ranked as the most troublesome (hard to control) weed for corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), sorghum [*Sorghum bicolor* (L.) Moench], and soybean [*Glycine max* (L.) Merr.] in the United States and Canada (Van Wychen 2020, 2022), whereas *A. tuberculatus* was reported as the second most troublesome weed in corn and soybean (Van Wychen 2020, 2022).

Genetic diversity, phenotypic plasticity, rapid growth rate, and a wider emergence window contribute to the troublesome nature of ASW. *Amaranthus palmeri* and *A. tuberculatus* can grow by 0.21 and 0.16 cm per growing degree day, respectively (Horak and Loughin 2000), reaching more than 1-m tall within 6 wk after emergence (Sellers et al. 2003). Moreover, these weeds have a multiple emergence pattern and can emerge throughout the crop growing season (Franca 2015). If uncontrolled, *A. palmeri* infestations can reduce yields by as high as 91% in corn (8 plants m^{-2}; Massinga et al. 2001), 79% in soybean (8 plants m^{-2}; Bensch et al. 2003), 77% in cotton (17 plants m^{-2}; Fast et al. 2009), 63% in sorghum (2 plants m^{-2}; Moore et al. 2004), and 77% in dry edible beans (*Phaseolus vulgaris* L.) (2 plants m^{-2}; Miranda et al. 2021). Uncontrolled infestations of *A. tuberculatus* can reduce corn yields by 74% (310 plants m^{-2}; Steckel and Sprague 2004) and soybean yields by 56% (8 plants m^{-2}; Bensch et al. 2003). Moreover, ASW are prolific seed producers and can produce more than 250,000 seeds plant^{-1} (Anderson 2023; Sellers et al. 2003), which is enough to severely infest 1 ha of land. Thus, effective management of ASW is essential to reduce interference and crop yield loss.

The evolution of multiple herbicide resistant *A. palmeri* and *A. tuberculatus* and their widespread occurrence is a challenge for crop producers (Beckie 2020; Kaur 2024; Westwood et al. 2018). *A. palmeri*, *A. retroflexus*, *A. hybridus*, and *A. tuberculatus* have been reported resistant to nine, five, two, and seven herbicides with distinct sites of action, respectively, across the United States and Canada (Heap 2024). *Amaranthus palmeri* and *A. tuberculatus* are dioecious species with obligate outcrossing reproductive biology (Jianyang et al. 2012; Legleiter and Johnson 2013) that increases chances of disseminating herbicide-resistance alleles among populations (Jhala et al. 2021; Sarangi et al. 2017). Furthermore, the rapid growth habit of ASW reduces the window of herbicide application for their effective control, which demands adoption of an integrated approach for managing multiple herbicide resistant ASW (Kumar et al. 2023a; Stephens et al. 2024).

Cover crops (CCs) can be an effective tool for integrated management of herbicide-resistant and herbicide-susceptible weeds in crop production systems (Bunchek et al. 2020; Kumar et al. 2020; Kumari et al. 2023a, 2023b). CCs suppress weeds before and after their termination. Before termination, CCs compete with weeds for nutrients, water, and space (Mirsky et al. 2017; Sias et al. 2023; Smith et al. 2015), whereas after termination, CCs reduce the germination and growth of weeds by blocking the sunlight and reducing soil temperature (den Hollander et al. 2007; Rosario-Lebron et al. 2019). In a 2-yr study in Arkansas, USA, Palhano et al. (2017) reported an 83% reduction in *A. palmeri* cumulative emergence in a cotton field due to presence of cereal rye (*Secale cereale* L.) CC residues compared with no CC (NCC). In a 4-yr study in Missouri, USA, Cornelius and Bradley (2017) reported a 35% reduction in early-season *A. tuberculatus* density in soybean fields with the inclusion of cereal rye CC. Similarly, in a 2-yr multilocation study in the United States, Masiunas et al. (1995) reported 82% reduction in the emergence of *A. retroflexus* in tomato (*Solanum lycopersicum* L.) fields, and Reddy (2003) reported 37% reduction in *A. hybridus* emergence in soybean production fields in Mississippi, USA, due to cereal rye cover crop compared with NCC.

Weed suppression with CCs may vary with CC species, CC biomass production, weed species (Cornelius and Bradley 2017; Kumari et al. 2024; Palhano et al. 2017), CC planting and termination time (Mirsky et al. 2011), CC seeding rate (Bish et al. 2021), CC termination method (Nichols et al. 2020; Osipitan et al. 2019), and time after crop planting (Curran et al. 1994; Palhano et al. 2017). In a study conducted in Arkansas, cereal rye CC decreased *A. palmeri* density by 90% at 4 wk after planting (WAP) cotton compared with a 44% reduction at 8 WAP (Palhano et al. 2017). Similarly, in a Pennsylvania, USA, study, Curran et al. (1994) found that hairy vetch (*Vicia villosa* Roth) decreased *A. hybridus* density by 76% at 4 WAP corn compared with no reduction at 8 WAP. It is difficult to evaluate the effect of various CC management decisions on weed suppression in a single research study. Numerous independent studies have evaluated the impact of one or more CC management decisions on weed suppression.

A meta-analysis is needed to synthesize the results of different research studies (Osipitan et al. 2018, 2019). Meta-analyses have evaluated the role of CCs for suppressing weeds (Dong and Zeng 2024; Nichols et al. 2020; Osipitan et al. 2018, 2019; Weisberger et al. 2023), indicating that CCs can reduce weed biomass (Nichols et al. 2020; Osipitan et al. 2019) and density (Osipitan et al. 2019; Weisberger et al. 2023) (hereafter "weed biomass/density" refers to the biomass/density of the mixture of grass/broadleaf/sedge weeds unless specified). The effect of CCs on weed suppression is species specific, as some weed species are more susceptible than others (Crawford et al. 2018; Reddy 2003). In Illinois, USA, Crawford et al. (2018) reported that cereal rye and radish (*Raphanus sativus* L.) CCs reduced the broadleaf weed density (including ASW) but did not affect grass weed density. In Mississippi, Reddy (2003) reported a 50% reduction in *A. hybridus* density with cereal rye residues compared with conventionally tilled NCC plots, but no effect on other broadleaf weeds such as hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh], pitted morningglory (*Ipomoea lacunosa* L.), prickly sida (*Sida spinosa* L.), and sicklepod [*Senna obtusifolia* (L.) Irwin & Barneby]. Therefore, an evaluation of the effect of CCs on suppression of specific problematic weed species seemed necessary. The published meta-analyses studies have not evaluated the effect of CCs on individual weed species, especially ASW at different times during the crop-growing season. The objective of this meta-analysis was to evaluate the implications of CC management decisions (CC type, planting and termination methods, residue fate after termination, and in-season weed management plan) on density and biomass of the most common ASW (viz. *A. palmeri*, *A. retroflexus*, *A. hybridus*, and *A. tuberculatus*) at early (0 to 4 WAP), mid- (5 to 8 WAP), and late (>8 WAP) season crop growth stages in the growing season compared with no CC (NCC) in temperate regions, including the United States and Canada.

Materials and Methods

Literature Search and Data Extraction

The literature was conducted during December 2023 to March 2024 using Google Scholar, Scopus, and two weed science journals: *Weed Science* and *Weed Technology*. The keywords included "cover crop"/"cover crops"/"cover cropping"/ "rye"/"wheat"/"vetch"/ "brassica"/"barley"/"oat" AND "weed" OR "amaranth" OR "amaranthus" OR "pigweed" OR "Palmer" OR "waterhemp".

The search queries were targeted at article titles. The selection criteria were that CC studies had to: (1) be conducted in the United States or Canada; (2) include an NCC treatment for comparison; (3) report data on at least one of the four *Amaranthus* spp., viz. *A. palmeri*, *A. retroflexus*, *A. hybridus*, and *A. tuberculatus*; and (4) report at least one of the response variables (i.e., weed biomass

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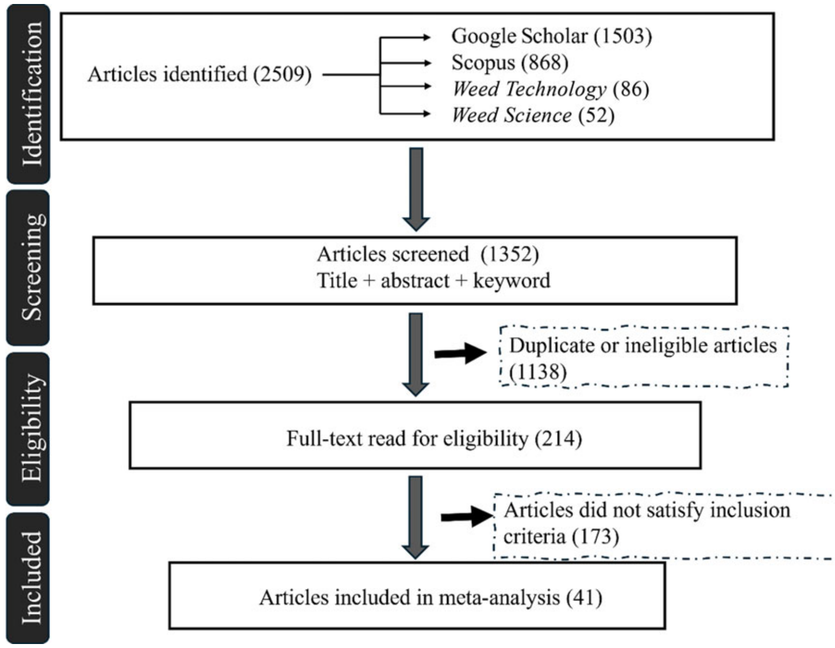

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Page et al. 2021) flow diagram explaining the systematic procedure used for selecting articles included in the meta-analysis.

and/or weed density) for both CC treatment and NCC control groups. Only studies conducted in the United States and Canada were included in this meta-analysis, as the abovementioned ASW are problematic in these two temperate countries.

The systematic literature search resulted in 2,509 published papers, of which 214 articles were selected for full-text reading after screening the titles and abstracts and removing the duplicates and articles that did not meet criteria (Figure 1). We found 41 studies that met the criteria. A total of 595 paired observations and the following data were extracted from these papers:

- Experimental data: experimental year, location, and replications.
- Soil data: soil series, texture, organic matter content, and soil pH;
- Crop data: crop name, planting time, seeding rate, plant population, irrigation (irrigated/rainfed), yield, in-season weed management strategies, and in-season herbicide application timings;
- CC data: CC name, type, planting and termination time, days between planting and termination, seeding rate, planting method, termination method, aboveground dry biomass accumulation, and residue fate after termination; and
- Weed data: common name, scientific name, weed data collection time (weeks after crop planting; WAP), and mean density and/or biomass for CC and NCC groups.

Meta-analysis: Overall Effect of CCs on Suppression of *Amaranthus* spp. Weed Density, and *Amaranthus* spp. Weed Biomass

Data analysis and visualization were performed in R software v. 3.6.2 (R Core Team 2021). The overall effect of CCs on *Amaranthus* spp. weed density (ASWD) and *Amaranthus* spp. weed biomass (ASWB) was determined by natural logarithm of the response ratios (treatment mean/control mean) (Hedges et al. 1999; Equation 1).

$$\ln(\mathrm{RR}) = \ln(X_t/X_c) \quad [1]$$

where $\ln(\mathrm{RR})$ is the natural logarithm of the response ratio and represents the individual effect sizes, X_t and X_c are the mean values of the response variable (i.e., ASWD or ASWB) for CC and NCC groups, respectively. Natural logarithmic transformation is required to remit the higher degree of variance from studies given the widespread temporal and spatial differences across the selected studies (Philibert et al. 2012).

In the final dataset, 78 observations had zero value for the means of either CC ($n = 44$) or NCC ($n = 34$) treatment. The response ratio cannot be computed if the treatment value is zero (Singh et al. 2023; Thapa et al. 2018a). Therefore, the zero values were converted to the lowest possible value, that is, 0.1 ($n = 47$, for the studies that reported mean values as decimals) or 1 ($n = 31$, for the studies that reported mean values as whole numbers). This method of using imputed values to calculate the response ratio can lead to biased and unrealistic values (Verret et al. 2017; Weisberger et al. 2019). However, a sensitivity analysis performed with and without the inclusion of imputed values indicated no significant bias with their inclusion. Therefore, the imputed values were included in the final analysis.

The majority of the 41 articles did not report within-study variations such as coefficient of variation, SE, or SD. Therefore, the standard variance approach of Hedges and Olkin (2014) cannot be used for weighting the individual effect sizes. As proposed by Adams et al. (1997), experimental replications were used to weight the individual effect sizes (Equation 2):

$$w_i = (N_t \times N_c)/(N_t + N_c) \quad [2]$$

where w_i is the weight of individual effect size for ith observation and N_t and N_c are the number of replications for the CC and NCC

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groups, respectively. Multiple effect sizes were calculated from studies reporting results from multiyear or multilocation experiments and/or examining more than one CC treatment sharing the same NCC control group. This approach could lead to dependency between effect sizes within and across studies. Therefore, a multilevel mixed-effects meta-analytic model was designed using the NLME package in R (Pinheiro et al. 2023; Singh et al. 2022, 2023; Thapa et al. 2018b; Van den Noortgate et al. 2013). In this model, effect sizes were treated as a fixed effect, study/site-year/common controls were nested as random effects, and w_i values served as weighting factors. Due to the lack of actual sampling variance measures, a cluster-based robust variance estimator was used to estimate SEs for mean effect sizes using the CLUBSANDWICH package in R (Pustejovsky 2022). These robust SEs were used to calculate 95% confidence intervals (CIs) for the weighted mean effect sizes (i.e., $\overline{\ln(RR)}$. The overall impact of CCs on ASWD or ASWB was deemed significant ($P < 0.05$) if the 95% CIs did not include zero. For interpretation, the mean effect sizes and their associated 95% CIs were back-transformed exponentially to represent the percentage change in responses (Equation 3):

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

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

Moderator Analysis: Effects of Potential Covariates on Overall CC Effects

A moderator analysis was performed to test the effect of potential covariates such as CC type, CC planting and termination method, CC residue fate, in-season weed management plan, and in-season herbicide application timings on overall effect sizes of CCs on ASWD and ASWB. Each covariate was divided into subgroups:

- *Amaranthus spp.*: *A. palmeri*/*A. hybridus*/*A. retroflexus*/ *A. tuberculatus*/mixed (mixed population of two or more of the previously mentioned *Amaranthus* species);
- *CC type*: grass/legume/brassica/mixture;
- *Cash crop type*: Corn [corn + sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*)]/cotton/soybean (soybean + edamame)/vegetable.
- *CC planting method*: drilled/broadcast/broadcast followed by (fb) incorporation;
- *CC termination method*: chemical/mechanical/winter kill/ integrated (integrated termination is the use of two or more termination methods simultaneously);
- *CC residue fate*: standing/rolled/incorporated;
- *Crop in-season weed management plan*: chemical/mechanical/untreated (untreated refers to no weed management); and
- *Crop in-season herbicide application timing*: preemergence/ postemergence/preemergence fb postemergence.

For each subgroup, separate effect sizes and SEs were calculated by treating each moderator variable as a single covariate in the primary multilevel mixed-effects meta-analytic model previously described. To reduce the likelihood of experiment-wise type I errors, 99% CIs were calculated for the moderator analysis. The mean CC effect was considered significant ($P < 0.01$) if the 99% CIs for each subgroup did not include zero. Furthermore, the subgroups were deemed significantly different from each other if their 99% CIs did not overlap (Singh et al. 2022, 2023; Thapa et al. 2018a).

Meta-regression Analysis

We conducted mixed-effects meta-regression analysis using the NLME package in R to determine the effect of CC biomass at termination as well as the time interval between CC termination and subsequent cash crop planting on ASWD and ASWB. In the meta-regression analysis, we used CC biomass at termination or the time interval between CC termination and subsequent crop planting as the fixed effect and set the study/site-year/common control as the nested random effects and w_i values as the weighting factor. CC biomass required for 50% ASWD and ASWB reduction was estimated using the intercept and slope coefficients from the fitted mixed-effects meta-regression model. Bubble plots were created for visualization of meta-regression analysis, where the size of a bubble was based on the sample size, this is, weights assigned for individual ln(RR). Furthermore, random effects were subtracted from individual effect sizes before bubble plots were created (Thapa et al. 2018a).

Publication Bias and Sensitivity Analysis

Density plots, which are an indirect and visual approach, were used to assess the distribution of individual effect sizes for each response variable (Basche and DeLonge 2017; Singh et al. 2022, 2023; Thapa et al. 2018a). Overall effect sizes were tested for robustness. The jackknife procedure for sensitivity analysis was used to determine studies that might have affected results (Philibert et al. 2012). In the jackknife procedure, one study at a time was systematically removed from the dataset, which was followed by rerunning the primary multilevel mixed-effects meta-analysis model each time to recalculate the overall effect sizes without the inclusion of that specific study.

Results and Discussion

Database Description

The selected studies were conducted from 1994 to 2024. Out of 41 articles that met our selection criteria, 40 were from the United States (one each from Iowa, North Carolina, and Pennsylvania; two each from Missouri and Tennessee; three each from Alabama, Illinois, Kansas, Michigan, Mississippi, and Nebraska; four from Georgia; five multistate studies; six from Arkansas) and one (Moore et al. 1994) from Ontario, Canada (Table 1). Soybean ($n = 15$; 14 soybean + 1 edamame) was the major crop studied, followed by cotton ($n = 13$), corn ($n = 5$; 4 field corn + 1 sweet corn), and vegetable crops [$n = 6$; cucumber (*Cucumis sativus* L.), onion (*Allium cepa* L.), pumpkin (*Cucurbita pepo* L.), southern pea [*Vigna unguiculata* (L.) Walp.], sweetpotato [*Ipomoea batatas* (L.) Lam.], and tomato]. One study (Wortman 2012) included three crops: corn, soybean, and sunflower (*Helianthus annuus* L.). Grass was the most common CC type, with 90% of studies ($n = 37$) including grass species either alone or as one of the treatments along with other CC types (Table 1). Legume CC species were found in 17 articles, followed by a mixture of grass and legumes ($n = 6$), and brassica species alone ($n = 4$). One study (Wortman 2012) had a three-way mixture of legume, brassica, and buckwheat (*Fagopyrum esculentum* Moench) CCs. Cereal rye was the most common CC species, with 80% of studies ($n = 33$) (Table 1).

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Table 1. List of studies included in the meta-analysis and moderator variables (weed data collection timing, cover crop [CC] functional group, planting method, termination method, residue fate, in-season weed management, in-season herbicide application timing, *Amaranthus* species, and cash crop type) information.

Reference	Location	Weed data collection timing[a]	CC type[b]	CC planting method[c]	CC Termination method[d]	CC Residue fate[e]	In-season weed management[f]	In-season herbicide application timing[g]	*Amaranthus* species[h]	Cash crop type[i]
Aulakh et al. (2012)	Shorter, AL	E, M	G, L	D	I	R	H, N	PRE, POST, PRE fb POST	PA	CT
Aulakh et al. (2013)	Shorter, AL	E	G, L	D	I	R	H, N	POST	PA	CT
Bish et al. (2021)	Columbia, MO	E, M	G	D	C	S	N	—	W	S
Burgos and Talbert (1996a)	Fayetteville and Kibler, AR	E	G, L, M	D	C	S	H, M, N	PRE	PA, RP	CR
Burgos and Talbert (1996b)	Kibler, AR	M	G	D	C	S	H, N	PRE fb POST	PA	V
Cornelius and Bradley (2017)	Columbia and Moberly, MO	E, L	G, L, B, M	D	C	S	N	—	W	S
Crawford et al. (2018)	Urbana, IL	E	G, B	D, BI	C	S	N	—	PA	S
Curran et al. (1994)	Rock springs, PA	E, M	L	D	M, C	I, R, S	H, N	PRE, PRE fb POST	SP	C
Currie and Klocke (2005)	Garden city, KS	L	G	D	C	S	H, N	PRE	PA	C
Davis (2010)	Urbana, IL	M	G, L	D	I	R, S	H, N	POST	W	S
Dearden (2022)	Ames and Burner, IA	M, L	G	D	C	S	H, N	PRE, POST, PRE fb POST	W	S
DeVore et al. (2012)	Marianna, AR	E, M, L	G	D	C	S	H	POST	PA	CT
DeVore et al. (2013)	Marianna, AR	E, M, L	G	D	C	S	H	POST	PA	S
Hand et al. (2019)	Berrien, Colquitt, Malcon, Worth, and Tift, GA	M, L	G	D	I	R	H	PRE fb POST	PA	CT
Hand et al. (2021)	Jackson, TN, and Ty Ty, GA	E, M, L	G	D	I	R	H, N	PRE, POST, PRE fb POST	PA	CT
Hay et al. (2019)	Manhattan, Hutchinson, and Ottawa, KS	E, M	G	D	C	S	N	—	PA, W	S
Koger and Reddy (2005)	Stoneville, MS	M	L	D	C	S	H, N	PRE fb POST	SP	CR
Koger et al. (2002)	Stoneville, MS	L	G	D	C	S	H, N	PRE, POST, PRE fb POST	PA	S
Loux et al. (2017)	13 sites across AR, IN, IL, MO, OH, and TN	M, L	G, M	D	C	S	H, N	PRE fb POST	PA	S
Masiunas et al. (1995)	Champaign, IL Lafayette, IN	E, M	G	D	I, M	R	N	—	RP	V
McCall (2018)	Manhattan, KS	E, M, L	G, L, M	D	C	S	H, N	PRE, POST, PRE fb POST	PA	S
Moore et al. (1994)	Woodstock, ON, Canada	E, M, L	G	D	I	R	N	—	RP	S
Norsworthy et al. (2016)	Keiser, AR	L	G	D	C	S	H	POST, PRE fb POST	PA	S
Ngouajio and Mennan (2005)	East Lansing, MI	E, M	G, L	BI	I, W	I, S	N	—	RP	V
Nunes et al. (2023)	Brooklyn, WI Carbondale, IL	M	G	D	C	S	H, N	PRE	M	S

(*Continued*)

Table 1. (*Continued*)

Reference	Location	Weed data collection timing[a]	CC type[b]	CC planting method[c]	CC Termination method[d]	CC Residue fate[e]	In-season weed management[f]	In-season herbicide application timing[g]	*Amaranthus* species[h]	Cash crop type[i]
	Rock Springs, PA Rossville, KS									
Oys (2022)	Mead and Clay Center, NE	E, L	G, L	D	C	S	H, N	POST	M, W	CR
Palhano et al. (2017)	Fayetteville, AR	E, M	G, L, B	D	C	S	N	—	PA	CT
Price et al. (2012)	Belta Mina and Shorter, AL	E, L	G	D	I	R	H, N	[j]	PA, RP	CT
Price et al. (2016)	Barbour, AL Macon, Seminole, and Worth, GA Calhoun and Lee, SC Tipton, TN	L	G	D	C	S	H	PRE fb POST	PA	CT
Reddy (2003)	Stoneville, MS	M	G	D	C	S	N	—	SP	S
Rogers (2017)	Middleton, MI	L	G	D	C, M	R, S	N	—	PA	S
Timper et al. (2011)	Tifton, GA	E	G	D	I, M	I, R	H	PRE fb POST	PA	CT
Treadwell et al. (2007)	Goldsboro, NC	L	M	D	M	I, R	N	—	M	V
Walters and Young (2010)	Carbondale, IL	L	G	BC	I	R	H, M, N	[j]	RP	V
Wang et al. (2008)	Laingsburg, MI	L	G, B	BC	M, W	I, S	N	—	RP	V
Webster et al. (2013)	Ideal and Chula, GA	E, L	G, L, M	D	I	R	N	—	PA	CT
Weisberger et al. (2024)	Walkinsville, GA	L	G, L	D	I	R	N	—	PA	CT
Wiggins et al. (2016)	Jackson, TN	M	G, L, M	D	C	S	H, N	[j]	PA	CT
Wiggins et al. (2017)	Jackson, TN	E	G, L	D	C	S	N	—	PA	S
Williams et al. (1998)	Ithaca, NE	E, M	G, L	D	C	S	N	—	M	S
Wortman (2012)	Mead, NE	E	M	BI	M	I, R	M	—	RP	CR, S

[a]E, early season (0–4 wk after crop planting); M, midseason (5–8 wk after crop planting); L, late season (>8 wk after crop planting).
[b]B, brassica; G, grass; L, legume; M, mixture.
[c]BC, broadcasting; BI, broadcasting followed by incorporation; D, drilling.
[d]C, chemical; I, integrated; M, mechanical; W, winterkill.
[e]I, incorporated; R, rolled; S, standing.
[f]H, herbicide; M, mechanical; N, no weed control method used.
[g]PRE, preemergence; POST, postemergence; PRE fb POST, preemergence followed by postemergence.
[h]M, mixed (mixed population of *Amaranthus* spp.); PA, Palmer amaranth (*Amaranthus palmeri*); RP, redroot pigweed (*Amaranthus retroflexus*); SP, smooth pigweed (*Amaranthus hybridus*); W, waterhemp (*Amaranthus tuberculatus*).
[i]CR, corn; CT, cotton; S, soybean; V, vegetable.
[j]Data were averaged across herbicide application timings and in-season weed management method.

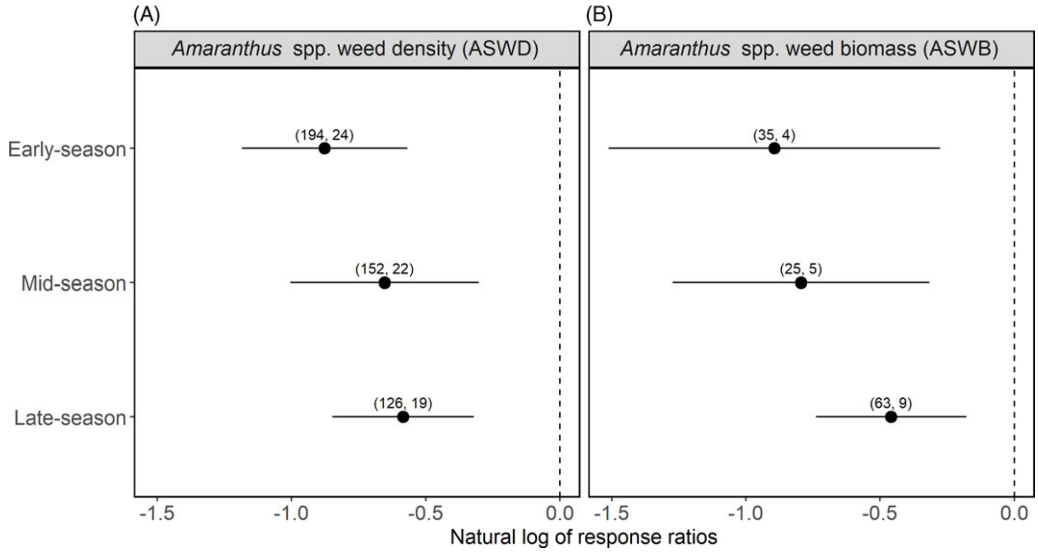

Figure 2. Overall effect of cover crops (CCs) on (A) *Amaranthus* spp. weed density (ASWD), and (B) *Amaranthus* spp. weed biomass (ASWB) at different weed data collection timings: (A) early season [0–4 wk after row crop planting (WAP)], (B) midseason (5–8 WAP), and (C) late season (>8 WAP), respectively. The numbers in the parenthesis represent the number of paired observations followed by the number of articles reporting each effect size. The vertical black dashed line, black dot, and horizontal solid black line represent zero effect, mean effect size (natural log of response ratio), and 95% confidence intervals (CIs), respectively. When the 95% CIs did not overlap or contain zero values, the effect sizes were deemed significantly different at a 5% level of significance.

ASW data were reported in 23 studies for early-, 23 for mid, and 21 for late- season (Table 1). Most studies evaluated *A. palmeri* ($n = 24$) followed by *A. retroflexus* ($n = 8$), *A. tuberculatus* ($n = 6$), *A. hybridus* ($n = 3$), and mixed ($n = 4$). Out of the 41 articles, 1 reported ASWB, 29 reported ASWD, and 11 reported both ASWD and ASWB. Drilling ($n = 36$) was the most common CC planting method (Table 1). Broadcasting (Walters and Young 2010; Wang et al. (2008) and broadcasting fb incorporation (Ngouajio and Mennan 2005; Wortman 2012) were used in two studies, whereas one study evaluated both drill planting and broadcasting by incorporation (Crawford et al. 2018; Table 1).

CCs were mostly terminated chemically (herbicides; $n = 26$), followed by mechanical termination (mower or roller-crimper; $n = 8$) (Table 1). An integrated method of termination (most commonly herbicides along with roller-crimper) was reported in 13 studies and winterkill in 2 studies (Nqouajio and Mennan 2005; Wang 2008). Davis (2010) terminated half of the treatments with herbicide and the other half with herbicide plus roller-crimper and averaged the ASWD data for both termination methods. CC residues were standing in 28 studies, rolled (lying on the soil surface) in 16, and soil incorporated in 6 (Table 1). Davis (2010) averaged ASWD data across standing and rolled CC. Sixteen of the 41 studies were nontreated (no crop in-season weed management tactics used), 16 had both nontreated and herbicide treatments, 6 used herbicides, and 1 used mechanical weeding as the in-season weed management practice during the crop season. Two studies included all three (nontreated, herbicide, and mechanical) practices of in-season weed management (Table 1).

Overall Effect of CCs on ASWD and ASWB

CCs reduced ASWD by 58% (95% CI = −69 % to −43%) in the early season, by 48% (95% CI = −63 % to −26%) in the midseason, and by 44% (95% CI = −57 % to −27%) in the late season compared with NCC (Figure 2). Germination of ASW seed is light-dependent, meaning that both the presence and quality of light influence the ability to germinate (Gallagher and Cardina 1998; Jha et al. 2010). ASW germination is higher in the presence of light than darkness (Carvalho and Christoffoleti 2006; Jha et al. 2010). Ratio of red:far-red light also affects ASW germination, with higher seed germination under red light than far-red light (Gallagher and Cardina 1998; Jha et al. 2010). CC residues act as a physical barrier blocking sunlight reaching the soil surface and also decrease the ratio of red:far-red light, thereby reducing the germination and density of ASW (Silva and Bagavathiannan 2023; Teasdale and Mohler 1993). Mean soil surface temperature and diurnal fluctuations in soil temperature also have a significant effect on germination of ASW (Jha et al. 2010; Steckel et al. 2004). In a study conducted in Illinois, Steckel et al. (2004) found that ASW germination increased by 5% when the temperature was raised from 20 to 25 C, and by 17% when the temperature was further increased to 30 C. Similarly, ASW germination increased by 15% by alternating the temperature ±40% of constant temperature in a sinusoidal fashion (Steckel et al. 2004). CC residues have a shading effect and enhance soil moisture content, which can lower daytime surface soil temperature from an average of 2 C (Blanco-Canqui and Ruis 2020) to as much as 6 C (Wagner-Riddle et al. 1994). CC residues can also decrease the diurnal fluctuations in the soil surface temperature (Blanco-Canqui and Ruis 2020; Teasdale and Mohler 1993).

CCs reduced ASWB by 59% (95% CI = −78 % to −24%) in the early season, by 55% (95% CI = −72 % to −27%) in the midseason, and by 37% (95% CI = −52 % to −16%) in the late season (Figure 2). CCs reduce ASW germination, which means fewer ASW plants per hectare to produce biomass. Additionally, the residue mulch hinders weed seedlings that have germinated from obtaining enough light for further growth and development (Silva and Bagavathiannan 2023). Dong and Zeng (2024) reported 85%, 52%, and 37% reduction in weed biomass during the early (at termination), mid- (within 50 d of termination), and late season (more than 50 d after termination), respectively. Mid- and late-season ASWB reduction in this meta-analysis is similar to weed biomass reported by Dong and Zeng (2024). However, they found higher weed biomass reduction (85%) during the early season

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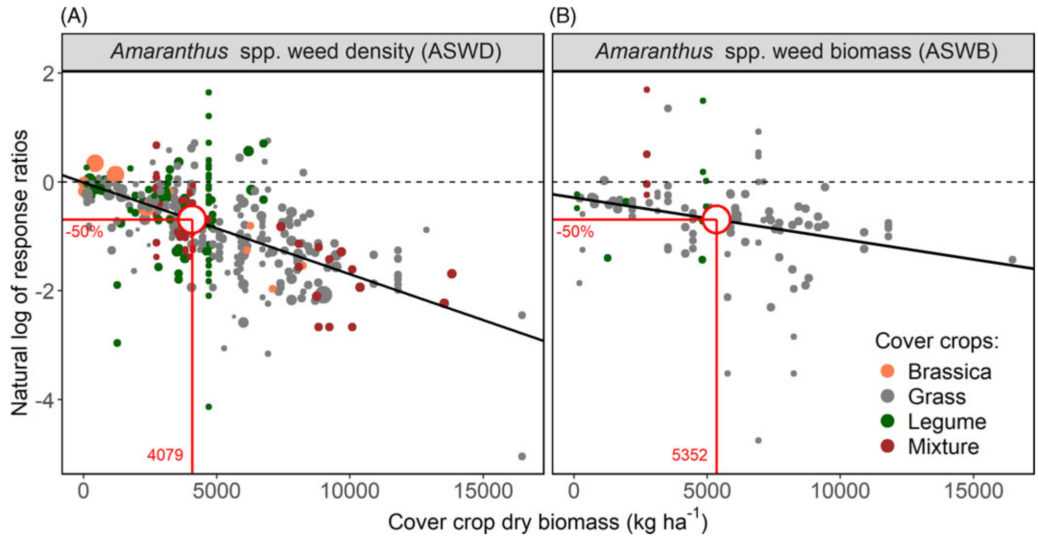

Figure 3. Bubble plots representing (A) *Amaranthus* spp. weed density (ASWD) and (B) *Amaranthus* spp. weed biomass (ASWB) natural log response ratio as a function of cover crop (CC) biomass (kg ha^{-1}). The color of the bubble represents the CC species, whereas the size of the bubble is based on the sample size (i.e., weights assigned for individual natural log response ratio). The black dashed line and solid black line represent zero effect and fitted regression model, respectively, whereas the solid red line indicates the 50% reduction in ASWD and ASWB with associated CC biomass values of 4,079 kg ha^{-1} and 5,352 kg ha^{-1}, respectively.

compared with 59% reduction in ASWB in this meta-analysis. This might be because "early season" has been defined as 0 to 4 WAP in this study compared with an earlier time of "at CC termination" by Dong and Zeng (2024).

Effect of CC Biomass and Time Interval between CC Termination and Subsequent Crop Planting on ASWD and ASWB

The regression analysis showed that CC biomass has a significant effect on the ASWD and ASWB (Figure 3). A linear regression model was the best fit for ASWD and ASWB (Table 2). CC biomass of 4,079 kg ha^{-1} was required to reduce the ASWD by 50% (Figure 3). Weisberger et al. (2023) reported that 6,600 kg ha^{-1} CC biomass is required for a 50% reduction in weed density, which is about 1.6 times the CC biomass required for ASWD reduction. This might be because along with ASW, Weisberger et al. (2023) included various weed species in their meta-analysis, such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], broadleaf signalgrass [*Urochloa platyphylla* (Munro ex C. Wright) R.D. Webster], browntop millet [*Urochloa ramosa* (L.) Nguyen], common ragweed (*Ambrosia artemisiifolia* L.), fall panicum (*Panicum dichotomiflorum* Michx.), ivyleaf morningglory (*Ipomoea hederacea* Jacq.), *I. lacunosa*, *S. spinosa*, yellow nutsedge (*Cyperus esculentus* L.), which had large-sized, high-mass seeds compared with ASW. It has been reported that weed emergence sensitivity to CC residue is inversely related to seed mass, with large-sized, high-mass seeds having more energy, allowing their seedlings to emerge through mulch (Ficks et al. 2022; Mirsky et al. 2011; Teasdale and Mohler 2000). In a study from Pennsylvania, Curran et al. (1994) found 60% reduction in *A. hybridus* density with hairy vetch CC compared with NCC, whereas there was no significant effect of CC on *P. dichotomiflorum* and *C. esculentus* density. Similarly, in Mississippi, Reddy (2003) reported 37% reduction in *A. hybridus* density with cereal rye CC, whereas there was no reduction in density of *E. crus-galli*, *U. ramosa*, *I. lacunosa*, and *S. spinosa*. Moreover, susceptibility of weed species to allelochemical released by CCs is inversely related to weed seed mass (Liebman and Sundberg 2006; USDA-NRCS 2016).

With meta-regression analysis, it was found that CC biomass of 5,353 kg ha^{-1} can decrease the ASWB by 50% (Figure 3). In a meta-analysis, Nichols et al. (2020) found that 5,000 kg ha^{-1} of CC biomass can reduce the weed biomass by 75%, which is higher than required for a 50% reduction in ASWB. This might be because Nichols et al. (2020) included studies from the U.S. Midwest compared with our meta-analysis, which has a significant number of studies from the U.S. Southeast (Table 1). Rapid accumulation of heat units and high annual rainfall in the U.S. Southeast make it favorable for growth, development, and higher weed biomass accumulation (Reinhardt Piskackova et al. 2021; Weisberger et al. 2023). This results in higher CC biomass requirement for weed biomass reduction in the U.S. Southeast (Weisberger et al. 2023). Also, ASW have a higher biomass accumulation rate compared with common weed species such as common lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), and common cocklebur (*Xanthium strumarium* L.) (Seibert and Pearce 1993), which were included in the meta-analysis by Nichols et al. (2020) along with ASW. Therefore, higher CC biomass may be needed for ASWB suppression than for emergence/density suppression.

CCs normally do not produce 4,000 to 5,000 kg ha^{-1}, except in warm-humid (>7 USDA plant hardiness zone and >750-mm annual precipitation) and warm-semiarid (>7 USDA plant hardiness zone and <750-mm annual precipitation) agroecozones (Ruis et al 2019). Ruis et al. (2019) found that CCs produced >4,000 kg ha^{-1} biomass about 74% and 50% of the time in warm-humid and warm-semiarid regions, respectively. However, CC management decisions, especially the time of planting and termination, need to be modified to achieve this level of CC biomass in mild-humid (USDA plant hardiness zones 5 to 7 and >750-mm annual precipitation) and cold-humid (USDA plant hardiness zone <5 and >750-mm annual precipitation) regions (Nichols et al. 2020; Ruis et al. 2019). CCs can be planted early by interseeding in standing crops in the fall season (Caswell et al.

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Table 2. Estimated coefficients from the linear meta-regression model between cover crop (CC) biomass and time between CC termination and subsequent crop planting as predicator variable and *Amaranthus* spp. weed density (ASWD) and *Amaranthus* spp. weed biomass (ASWB) as response variables.

Predictor	Response	Intercept	Slope	*N*	r^2	P-value
CC biomass	Density	−0.0053	−0.00017	360	0.298	<0.0001
	Biomass	−0.2884	−0.00007562	110	0.486	0.0568
Time between CC termination and subsequent crop planting	Density	−1.2162	0.21158	454	0.64	0.023
	Biomass	−0.5638	−0.03065	123	0.635	0.71

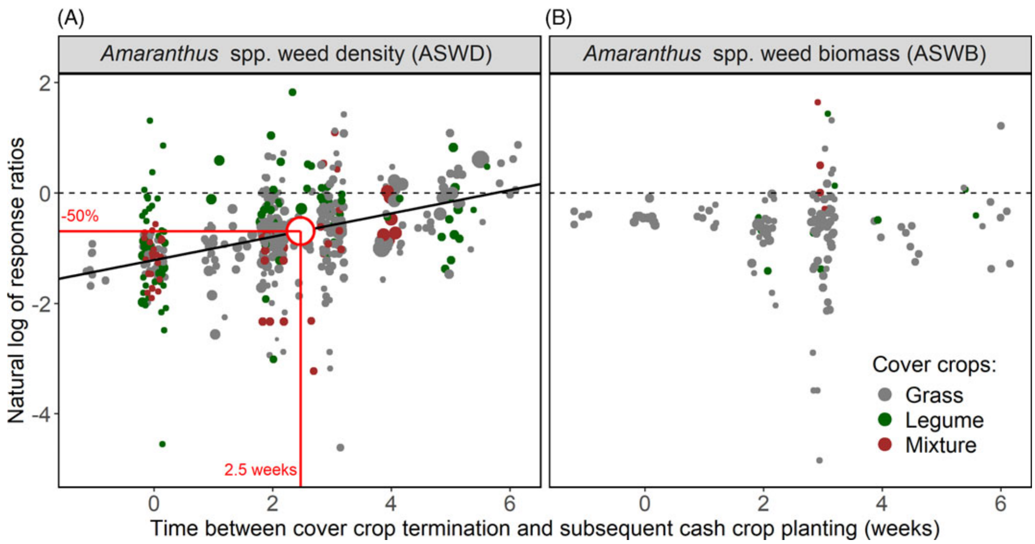

Figure 4. Bubble plots representing (A) *Amaranthus* spp. weed density (ASWD) and (B) *Amaranthus* spp. weed biomass (ASWB) natural log response ratio as a function of time interval (weeks) between cover crop (CC) termination and subsequent crop planting. The color of the bubble represents the CC species, whereas the size of the bubble is based on the sample size (i.e., weights assigned for individual natural log response ratio). The black dashed line and solid black line represent zero effect and fitted regression model, respectively, whereas the solid red line indicates the 50% reduction in ASWD with associated CC termination and subsequent crop planting value of 2.5 wk. The regression model was not significant for ASWB.

2019; Curran et al. 2018), resulting in higher biomass accumulation. In a study conducted in Pennsylvania, Mirsky et al. (2011) found planting cereal rye in the last week of August resulted in 12% more biomass at termination compared with planting in the last week of September, and 56% more biomass compared with planting in mid-October. Similarly, in a study in Nebraska, USA, Carmona et al. (2022) reported a 316% increase in a cereal rye + oat (*Avena sativa* L.) CC mixture biomass at termination with mid-September planting compared with mid-October planting.

The regression model for the time interval between CC termination and subsequent crop planting and ASWB was not significant (P = 0.71) (Figure 4). There was a significant linear ($r^2 = 0.64$; P = 0.023) relationship for the time interval between CC termination and subsequent crop planting and ASWD. Greater ASWD reduction was achieved when CCs were terminated closer to the time of subsequent crop planting. The regression analysis suggested that CCs should be terminated no earlier than 2.5 wk before crop planting to reduce the ASWD by 50% or more (Figure 4). This might be because delaying CC termination close to crop planting time allows CCs to accumulate more biomass. In a study conducted in Virginia, USA, Kumar et al. (2023b) found a 139% increase in rapeseed or canola (*Brassica napus* L.) CC biomass when terminated at corn planting compared with terminating 4 wk before corn planting. Similarly, in a Nebraska study, Carmona et al. (2022) reported 95% increase in cereal rye + oat CC biomass when terminated at soybean planting compared with terminating 2 wk before planting. Adoption of the "planting green" practice wherein CCs are terminated at or sometime after crop planting can further facilitate delayed termination and higher CC biomass accumulation (Grint et al. 2022; Reed et al. 2019). However, delaying CC termination can result in reduced crop yield because of nutrient immobilization, especially following grass CC species (Lacey et al. 2023; Roth et al. 2023); increased incidence of seedling diseases (Acharya et al. 2017, 2020, 2022); and depletion of soil moisture (Qin et al. 2021). In Nebraska, Almeida et al. (2024) reported 15% to 76% reduction in corn yield when cereal rye termination was delayed by 3 wk, but no negative effect on corn yield with delayed hairy vetch termination. In a Pennsylvania study, Reed et al. (2019) found 5% to 10% reduction in corn yield with a 4-wk delay in cereal rye termination. Liebl et al. (1992) reported 21% reduction in soybean yield with cereal rye termination delayed by 2 wk in Illinois. However, neutral (Denton et al. 2023; Duiker and Curran 2005; Reed et al. 2019) and positive effects (Marcillo and Miguez 2017; Overmyer et al. 2023) of delayed CC termination on crop yield have also been reported.

Effect of CCs on Individual Amaranthus Species Density and Biomass

The 99% CIs for all the ASW overlapped at each respective data-collection timing (Figure 5), indicating no significant statistical differences among them. The four ASW evaluated in this meta-analysis have very similar seed size and temperature and light requirements for germination (Gallagher and Cardina 1998; Jha

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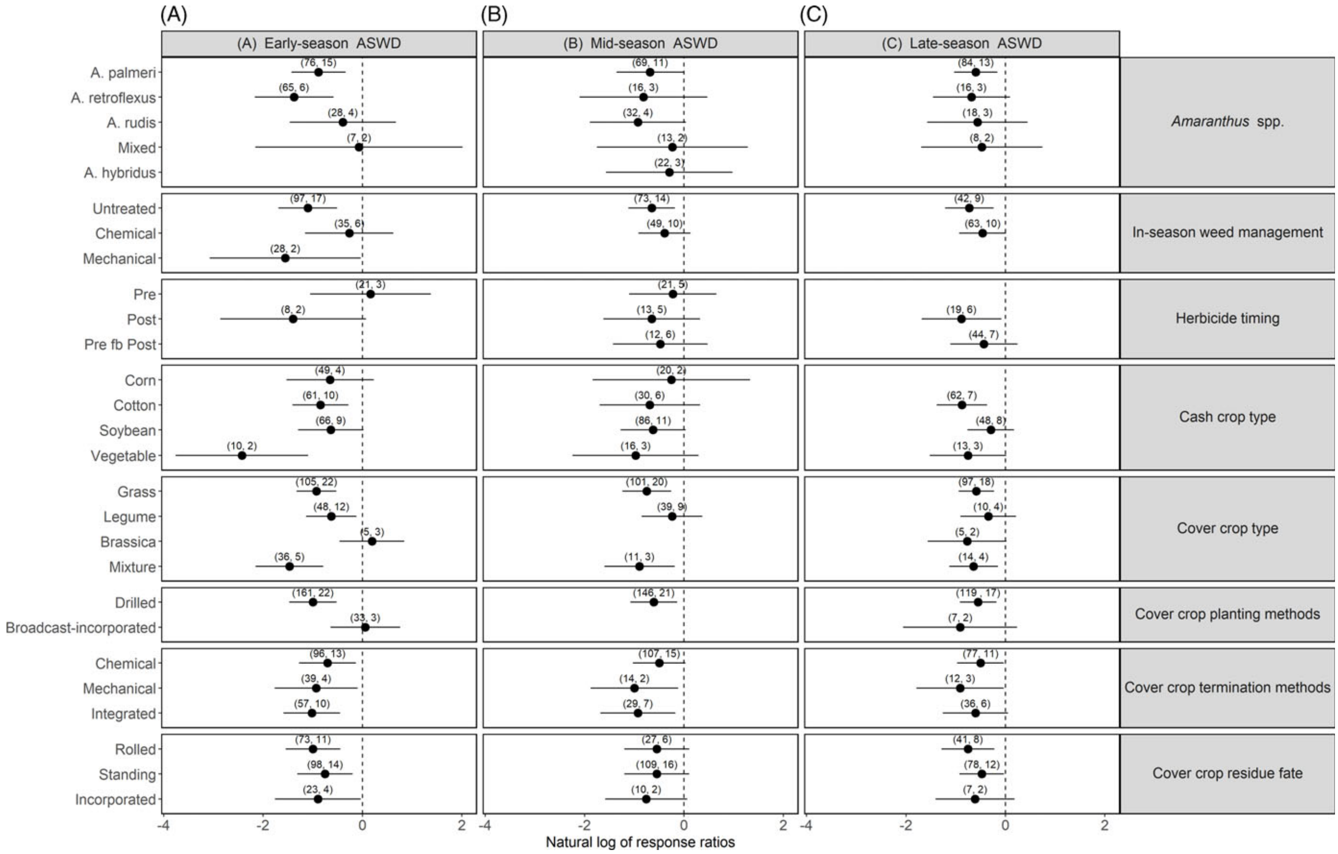

Figure 5. The effect of cover crops (CCs) on *Amaranthus* spp. weed density (ASWD) in (A) early season [0–4 wk after row crop planting (WAP)], (B) midseason (5–8 WAP), and (C) late season (>8 WAP) as impacted by individual *Amaranthus* spp., cash crop type, crop in-season weed management strategy, herbicide application timing, CC functional group, planting method, termination method, and residue fate. The numbers in parentheses represent the number of paired observations followed by number of articles reporting each effect size. The vertical black dashed line, black dot, and horizontal solid black line represent zero effect, mean effect size (natural log of response ratio), and 99% confidence intervals (CIs), respectively. When the 99% CIs did not overlap or contain zero values, the effect sizes were deemed significantly different at 1% level of significance.

et al. 2010; Steckel et al. 2004). CCs decreased *A. palmeri* density by 59% (99% CI = −76% to −29%) in the early season, 50% (99% CI = −74% to −1%) in the midseason, and 45% (99% CI = −64% to −15%) in the late season compared with NCC (Figure 5). CCs reduced *A. retroflexus* density by 75% (99% CI = −76% to −29%) in the early season, but had no effect in mid- and late season (Figure 5). Similarly, there was no effect of CCs on *A. tuberculatus* and mixed-group density and *A. palmeri* biomass at any data-collection timings. These results may be attributed to the significantly larger number of observations and studies reporting *A. palmeri* density for all three timings (early [76, 15], mid- [69, 11], and late season [84, 13]) and *A. retroflexus* density in the early season (65, 6) compared with other ASW (Figure 5). The greater volume of data likely provided more robust and reliable estimates of the effect of CCs on *A. palmeri* density at all timings and *A. retroflexus* density in the early season compared with other ASW. There were not enough observations to evaluate the effect of CC on biomass of ASW other than *A. palmeri*.

Effect of Cash Crop Species, In-Season Weed Management, and Herbicide Application Timing on ASWD and ASWB Suppression by CCs

CCs did not reduce ASWB in cotton and soybean in the late season, and there was not enough data observation for other crops. CCs reduced ASWD in cotton by 57% (99% CI = −75% to −25%) in the early season and 58% (99% CI = −75% to −31%) in the late season (Figure 5) compared with NCC. CCs also decreased ASWD in vegetable crops by 92% (99% CI = −98% to −66%) in the early season, whereas there was no effect in mid- and late season. In soybean, CCs significantly reduced ASWD by 47% in the early season ($P = 0.02$) and 46% in midseason (0.026) at the 95% CI level; however, these effects were not significant at the 99% CI level. Whereas in corn, CCs did not affect ASWD at any data-collection timing. This lack of effect may be due to the limited number of studies reporting ASWD data for corn ($n = 4$ for early, 2 for mid-, and 1 for late season) and the relatively low average CC biomass in these studies (2,641 kg ha^{-1}). Additionally, the rapid canopy development in corn may overshadow the weed-suppression benefits provided by CCs, effectively masking their impact on ASW. The influence of CCs on weed suppression may depend on the canopy development of the subsequent cash crop (Wortman 2012). However, the interaction between cash crop canopy and CC effects on ASW has not been adequately studied, highlighting the need for further research to better understand this relationship.

In nontreated in-season weed management treatments, CCs reduced ASWD by 67% (99% CI = −82% to −40%) in the early season, 48% (99% CI = −67% to −17%) in the midseason, and 52% (99% CI = −70 % to −21%) in the late season compared with NCC (Figure 5). The effect of CCs on ASWD was not significant (CI = 99%) when herbicides were used for in-season weed management (P-values of 0.45, 0.06, and 0.02 for early, mid-,

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and late season, respectively). Crop in-season herbicide use kills the weeds in both CC and NCC treatments and confounds the effect of CCs on weed management. Although CCs did not affect ASWD when herbicides were used during crop season, CCs may reduce the selection pressure for herbicide resistance by decreasing the number of ASW plants exposed to postemergence herbicides. In a study conducted in Delaware and Pennsylvania, Bunchek et al. (2020) found that cereal rye + crimson clover (*Trifolium incarnatum* L.) and cereal rye + hairy vetch mixtures reduced the number of *A. hybridus* exposed to postemergence herbicide by approximately 50% and 30% compared with NCC, respectively. Moreover, sole reliance on CCs for season-long ASW management is not recommended, because CCs are not able to provide complete ASW control and seed production by uncontrolled ASW can increase the ASW infestation in the upcoming years (Dearden 2022; Norsworthy et al. 2016). Osipitan et al. (2019) reported that the use of herbicides can supplement the weed suppression provided with CCs. In mechanically weeded treatments, CCs decreased ASWD by 79% (99% CI = −95 % to −3%) compared with NCC in the early season. However, there were not enough articles to evaluate the effect of CCs under mechanical weeding in mid- and late season. Furthermore, the effect of CCs on early-season ASWD reduction was significant in the mechanically weeded treatment but not in the herbicide treatment. This might be because mostly residual herbicides are used for early-season weed control, which does not allow ASW to germinate for a certain period, whereas mechanical weeding manages only the emerged ASW plants and does not have residual activity, so the ASW that emerge after mechanical weeding require additional management options.

The timing of herbicide application (preemergence, postemergence, and preemergence fb postemergence) did not influence the effect of CCs on ASWD during early and midseason (Figure 5). There were no data points for evaluating the effect of CCs on ASWD for preemergence-only treatment in the late season. Although CCs reduced ASWD by 35% for preemergence fb postemergence herbicide treatment in the late season, it was not significant (P-value = 0.11; 99% CI = −67% to 27%) compared with NCC. Whereas CCs reduced ASWD by 59% (99% CI = −81% to −8%) in postemergence-only treatment compared with NCC in the late season. This might be because ASW have a long window of emergence (Franca 2015), and most of the postemergence herbicides used in early to midseason did not affect the emergence of ASW in the late season, as they do not have soil-residual activity. Whereas preemergence herbicides in preemergence fb postemergence herbicide programs have soil-residual activity and do not allow weeds to germinate, thus masking the effect of CCs (Norsworthy et al. 2016). In Arkansas, Norsworthy et al. (2016) found that compared with NCC, cereal rye CCs reduced ASWD by 44% in postemergence-only treatment in late season (19 to 24 WAP), but there was no effect of CCs in the preemergence fb postemergence herbicide program. Similarly, in a study conducted in Iowa, Dearden (2022) reported a 41% decrease in late-season (10 WAP) ASWD with cereal rye CC in postemergence-only treatment compared with NCC, whereas the decrease in ASWD was 27% for the preemergence fb postemergence herbicide program. The observations were not sufficient to assess the effect of CCs on ASWB under various in-season weed management practices and herbicide application timings.

Effect of CC Type and Planting Method on ASWD and ASWB

Grass CCs decreased ASWD by 60% (99% CI = −73% to −41%) in the early season, 53% (99% CI = −71% to −23%) in the midseason, and 44% (99% CI = −61% to −20%) in the late season compared with NCC (Figure 5). Similarly, the CC mixture reduced ASWD by 77% (99% CI = −88% to −55%) in the early season, 59% (99% CI = −80% to −17%) in the midseason, and 47% (99% CI = −68% to −14%) in the late season (Figure 5). The mixtures had statistically similar ASWD reduction compared with grass CC species. This might be because out of eight studies evaluating CC mixture, seven included grass CC as a part of the mixture. Legume CCs decreased ASWD by 47% (99% CI = −68% to −11%) in the early season with no effect in the mid- (P = 0.31) and late season (P = 0.12) (Figure 5). The legume CC decomposes faster due to a low C:N ratio, leading to relatively less weed-suppression benefits in the mid- and late season (Palhano et al. 2017). A higher C:N ratio is required to increase the duration of ASW suppression (Pittman et al. 2020). CC residue with C:N ratio of 9:1 to 16:1 suppressed *A. retroflexus* by 50% in the early season (2 to 4 WAP), whereas a C:N ratio of >20:1 was required for 50% suppression of *A. retroflexus* in midseason (6 WAP) (Pittman et al. 2020). Unlike leguminous CCs, grass CCs have a high C:N (>20:1), helping them provide relatively longer duration of weed suppression (Cornelius and Bradley 2017; Palhano et al. 2017).

There were not enough data to evaluate the effect of brassica CCs on midseason ASWD. However, brassica CCs did not affect ASWD in the early (P = 0.45) and late season (P = 0.02) (Figure 5). This might be because the average biomass of brassica CCs was very low (1,500 kg ha^{-1}) for studies that reported ASWD for the early season included in this meta-analysis (Cornelius and Bradley 2017; Crawford et al. 2018; Palhano et al. 2017). One study had higher average biomass (6,931 kg ha^{-1}), but CC residues were incorporated in the soil before subsequent crop planting, resulting in a lack of mulch effect (Wang et al. 2008). In addition, Wang et al. (2008) recorded ASWD data for the late season (8 to 10 WAP) when the weed suppressive potential of CCs is relatively lower, as some of the CC biomass had been decomposed.

Grass species CCs reduced the ASWB by 63% (99% CI = −85% to −6%) and 53% (99% CI = −74% to −16%) in early and midseason, respectively. However, unlike ASWD, the effect of grass CCs on ASWB in the late season was not significant (CI = 99%; P = 0.04). This might be because higher CC biomass is required for ASWB reduction compared with ASWD (Figure 3). CC residue decomposes with time (Adhikari et al. 2024; Thapa et al. 2022), resulting in less biomass available for ASWB suppression during the late season. The data were not sufficient to evaluate the effect of other CC types on ASWB.

Drill planting of CCs decreased the ASWD by 63% (99% CI = −77% to −41%), 46% (99% CI = −66% to −13%), and 42% (99% CI = −60% to −17%) in early, mid-, and late season, respectively (Figure 5). However, CCs planted through broadcasting fb incorporation did not affect ASWD, indicating that drilling CCs is better for reducing ASWD than the broadcasting fb incorporation method. This might be because drill-planted CCs germinate early and have better stand establishment compared with broadcasting fb incorporation (Brennan and Leap 2014; Noland et al. 2018). In a study conducted in California, USA, Brennan and Leap (2014) found that broadcast fb incorporation had 33% to 50% lower CC stand compared with drill planting at 2 wk after planting; however, CC biomass was not measured in that study. Moreover, incorporation can place the seeds deep in the soil, leading to delayed germination (Brennan and Leap 2014). Drill-planted CCs also reduced the ASWB by 43% (99% CI = −66% to −7%) and 42% (99% CI = −60% to −17%) in the mid- and late season, respectively. However, the effect of drill planting CC on ASWB in the early season and other planting methods for early, mid-, or late season was not evaluated due to the limited number of observations.

Effect of CC Termination Method and Residue Fate on ASWD and ASWB

Throughout the cropping season, the effect of CCs on ASWD and ASWB did not differ by method of termination (mechanical, chemical, and integration) (Figure 5). Mechanically, chemically, and integrated terminated CC reduced ASWD by 50% to 64% in the early season, by 39% to 63% in the midseason, and by 39% to 60% in the late season (Figure 5). Chemical and integrated termination reduced ASWB by 40% (99% CI = −61% to −8%) and 69% (99% CI = −74% to −62%) in the midseason, respectively. There were not sufficient observations to evaluate the winterkill termination method. Osipitan et al. (2019) reported no difference in weed density/biomass with chemical or mechanical termination of CCs. However, crop yield can vary with different termination methods despite similar weed control (Curran et al. 1994; Masiunas et al. 1995). For example, CC regrowth following termination with a mower (mechanical termination) can result in competition with crop leading to subsequent yield loss (Carrera et al. 2004; Masiunas et al. 1995). In a Pennsylvania study, Curran et al. (1994) reported 25% corn yield loss following mower-terminated hairy vetch compared with chemical termination. Similarly, in a multistate study, Masiunas et al. (1995) found 12% lower tomato yield in mowed cereal rye plots compared with herbicide-terminated plots. Therefore, the termination method should be selected based on efficacy of CC termination.

The data for evaluating the fate of CC residue on ASWB were limited. CC residue fate as incorporated, rolled, or standing decreased ASWD in the early season; incorporated CC decreased ASWD by 59% (99% CI = −83% to −3%), rolled by 63% (99% CI = −79% to −36%), and standing by 53% (99% CI = −73% to −18%) (Figure 5). Osipitan et al. (2019) reported 63% and 57% weed suppression after 2 to 5 wk of CC termination with CC residue lying on the soil surface (rolled/standing) and incorporated in the soil, respectively. Standing (38%; 99 CI = −60% to −3%) and rolled (53%; 99% CI = −72% to −20%) CC decreased ASWD during the late season compared with NCC. ASWD suppression with incorporated CC residue was observed only in the early season. Similar results have been observed by Curran et al. (1994) in Pennsylvania, where soil-incorporated hairy vetch CC reduced *A. hybridus* density only in the early season (4 WAP). This might be due to the release of allelochemicals following incorporation of CC residues (Rice et al. 2012; Teasdale et al. 2012), whereas allelochemicals either leach down with rain/irrigation water or undergo decomposition by late season, becoming ineffective for weed suppression (An et al. 2002; Rice et al. 2012; Teasdale et al. 2012). In a study conducted in Maryland, USA, Teasdale et al. (2012) found that cereal rye incorporated in soil inhibited *A. hybridus* germination for 2 wk after incorporation, a period that coincided with peak allelochemical levels in the soil. However, it is difficult to measure the specific role of allelochemicals for weed suppression under field conditions (Silva and Bagavathiannan 2023; Sturm et al. 2018).

Publication Bias and Sensitivity Analysis

The distribution of individual effect sizes representing CC effects on early-, mid-, and late-season ASWD and ASWB is presented in Figure 6. The histogram and kernel density plots show that the individual effect sizes followed a normal symmetrical distribution, which is indicative of no publication bias. In all cases, the peak of the kernel density plots centered toward slightly negative response ratio values, indicating that the CCs exhibit weed suppressive ability for *Amaranthus* spp. throughout the subsequent crop season. Moreover, sensitivity analysis performed using the jackknife procedure showed that no single study appeared to have an influential effect on the mean effect sizes (Figures 7 and 8). Thus, the overall effect size estimates of CCs for early-, mid-, and late-season ASWD and ASWB obtained in this meta-analysis are robust compared with other response variables.

Limitations and Factors to Consider while Interpreting Results

- A systematic and extensive search was executed to include studies conducted in the United States and Canada comparing CC against NCC for ASWD, and ASWB. However, it is possible that some studies might have been missed that were not indexed/published in the searched databases/journals or had keywords other than those targeted.
- This meta-analysis includes 41 studies that collectively assess the influence of CCs on ASW. More studies would further enhance data robustness. However, many studies have reported the effects of CCs on overall weed density and biomass, often lacking differentiation among individual weed species. Given that CC impacts on weeds can vary by species, we recommend future research to provide species-specific effects to improve the precision and applicability of the findings.
- The emergence timing of ASW relative to CC termination and subsequent crop planting can significantly influence the effectiveness of CCs in suppressing ASW. However, most studies included in this meta-analysis did not report the relative emergence timing of ASW, limiting our ability to evaluate its impact on ASW suppression by CCs.
- CC biomass C:N ratio at termination affects decomposition rate (Adhikari et al. 2024; Thapa et al. 2022) and thereby has a significant effect on duration of weed suppression provided by CCs (Cornelius and Bradley 2017; Palhano et al. 2017; Pittman et al. 2020). We have evaluated the effect of CC functional groups (grass, legume, brassica, mixture) on duration of ASW suppression. However, depending on the CC growth stage at termination, CC biomass C:N ratio can vary for species within the same functional group (Otte et al. 2019; Thapa et al. 2022). In the 41 articles selected, the CCs were terminated at different growth stages, resulting in different C:N ratios. The selected articles, however, did not provide information on C:N ratio of CC biomass at termination; we therefore could not evaluate the effect of specific C:N ratio of CC biomass on ASW.
- The effect of CCs on crop yield was not evaluated in this meta-analysis, which is one of the factors driving decision making by crop growers. Yield data were not included, because existing meta-analyses have extensively evaluated the effect of CC on crop yield (Chahal and Van Eerd 2023; Marcillo and Miguez 2017; Peng et al. 2024). Therefore, the inclusion of crop yields from a smaller subset of CC studies included in this meta-analysis ($n = 41$) would not have given a robust conclusion.

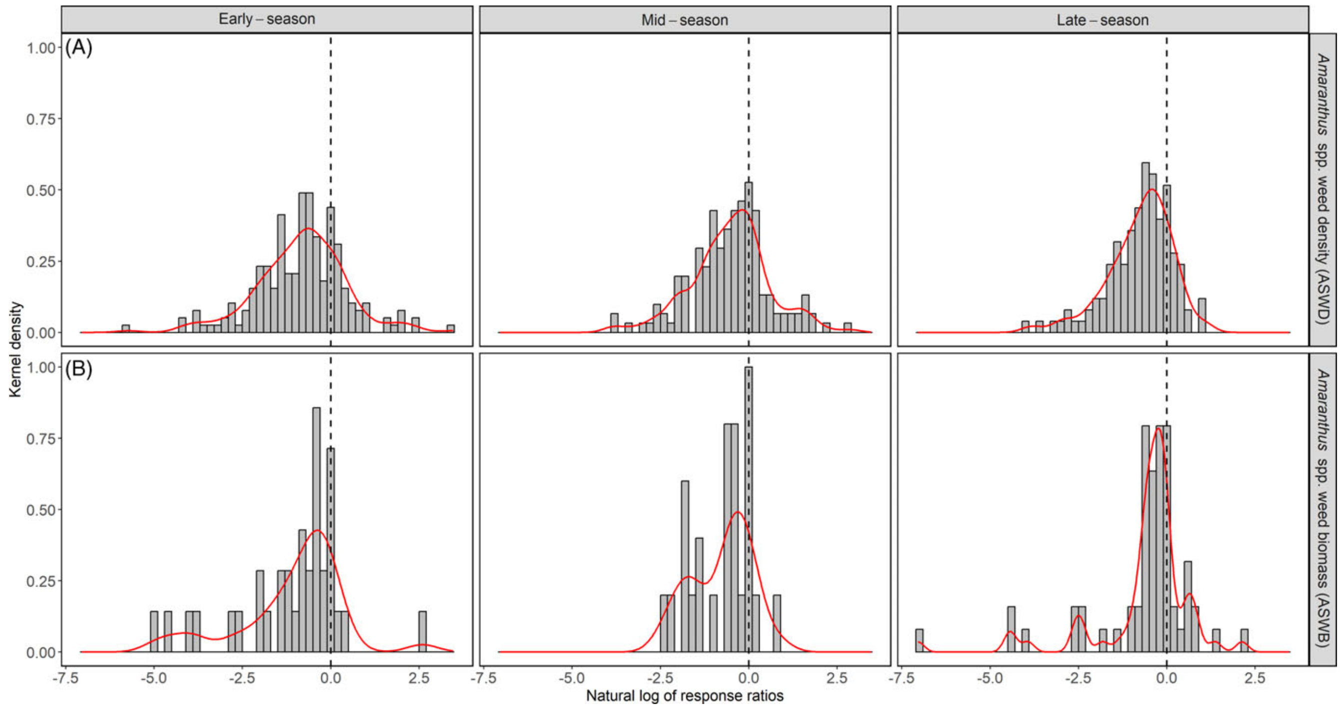

Figure 6. Density plot showing the distribution of individual effect sizes (natural log of response ratios) of (A) *Amaranthus* spp. weed density (ASWD), and (B) *Amaranthus* spp. weed biomass (ASWB) at early [0–4 wk after crop planting (WAP)], mid- (5–8 WAP) and late season (>8 WAP) weed data collection timing. The vertical dashed line represents the zero effect.

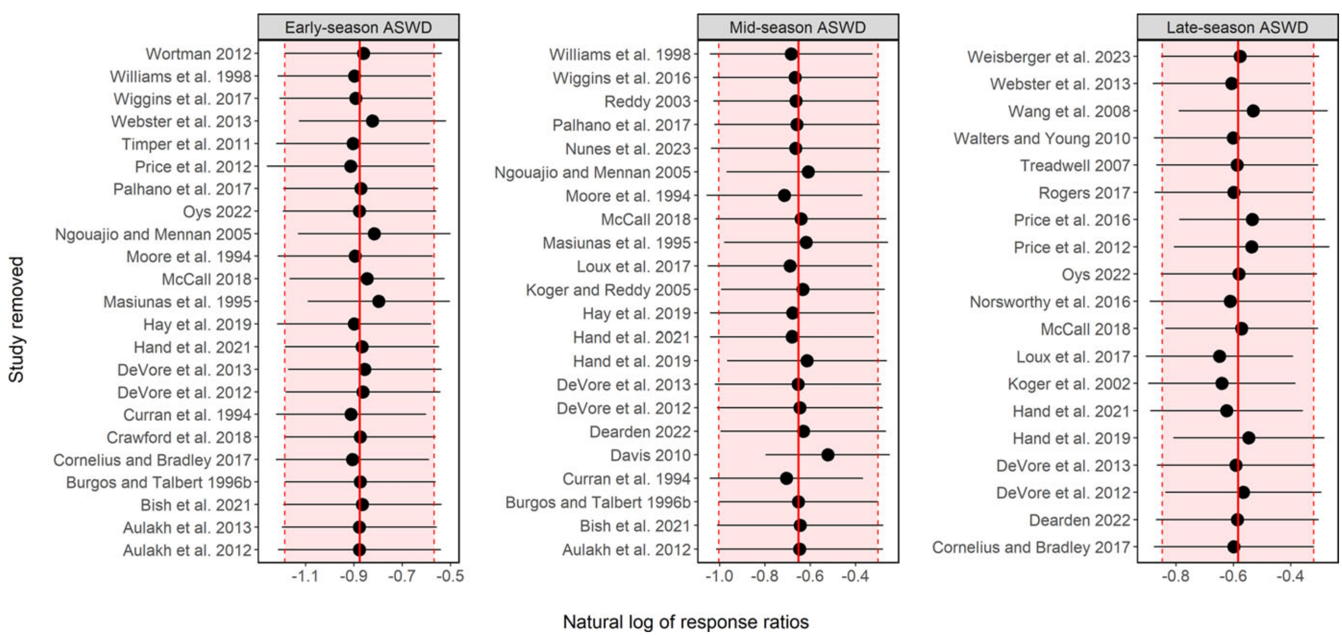

Figure 7. Sensitivity analysis conducted using jackknife procedure representing no impact of any single study removal on the overall effect sizes (log of response ratios [ln(RR)]) of cover crop (CC) effects on early-, mid-, and late-season *Amaranthus* spp. weed density (ASWD). The vertical solid and dashed red lines represent the mean and ±95% confidence intervals, respectively, of overall effect sizes with all the studies included in the analysis. The black dots and horizontal solid black lines represent the re-computed overall effect sizes and their ± 95% confidence intervals when the specific individual study was omitted from the analysis.

- The paired observations were <10 for some of the response variables in the moderator analysis (postemergence herbicide application timing and brassica CC for early-season ASWD; preemergence fb postemergence herbicide application timing and legume CC for late season), which limited our ability to estimate conclusive effect sizes for these subgroups.
- Most studies included in this meta-analysis did not report measures of within-study variation such as coefficient of variance, SD, or SE, which restricted us from calculating the sampling variance of the log response ratio (Nakagawa et al. 2023). Removing these studies from the dataset or accomplishing an unweighted analysis can potentially create

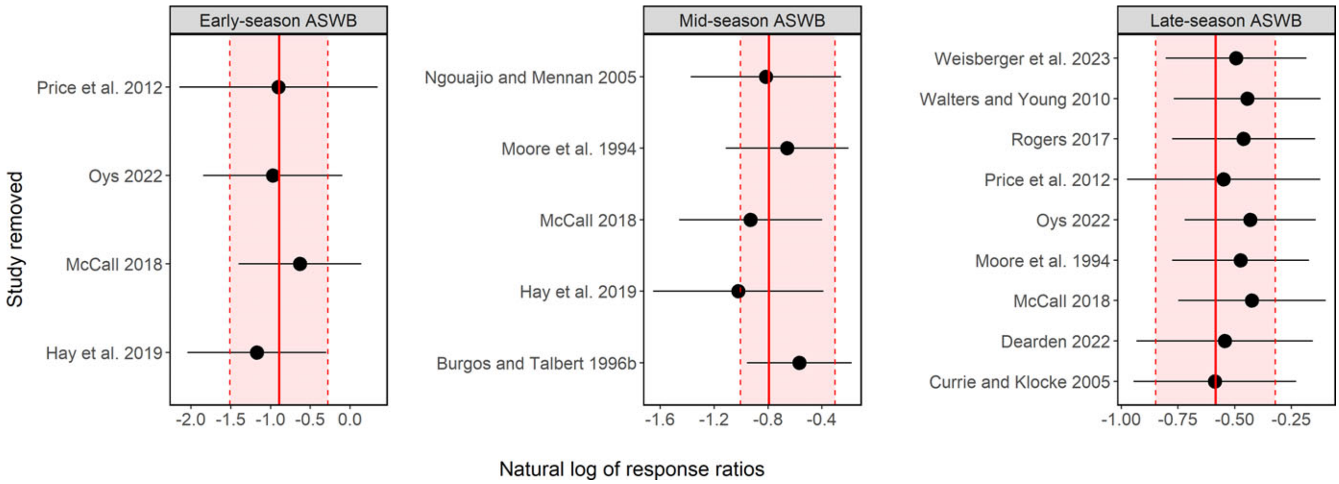

Figure 8. Sensitivity analysis conducted using *jackknife* procedure representing no impact of any single study removal on the overall effect sizes (log of response ratios [ln(RR)]) of cover crop (CC) effects on early-, mid-, and late-season *Amaranthus* spp. weed biomass (ASWB). The vertical solid and dashed red lines represent the mean and ±95% confidence intervals, respectively, of overall effect sizes with all the studies included in the analysis. The black dots and horizontal solid black lines represent the re-computed overall effect sizes and their ± 95% confidence intervals when the specific individual study was omitted from the analysis.

bias for estimating the overall effect size (Kambach et al. 2020). Therefore, we encourage the researchers to report measures of within-study variation in future studies.

Practical Implications

The results indicate that CCs can reduce ASWD by 58%, 48%, and 44% and ASWB by 59%, 55%, and 37% in early, mid-, and late season, respectively, compared with NCC. ASWD and ASWB suppression were found to be directly related to the amount of CC biomass accumulation. CC biomass of 4,079 kg ha^{-1} and 5,352 kg ha^{-1} could reduce 50% of ASWD and ASWB, respectively. Therefore, CC growers should adopt management strategies such as early planting and delayed termination that promote higher CC biomass production (>4,000 to 5,000 kg ha^{-1}) for effective ASW suppression. The results suggest that CC should be terminated as close as possible to subsequent crop planting to achieve higher ASWD suppression. However, other factors such as availability of soil moisture, amount of CC biomass, and optimum planting time of crop should be considered while deciding CC termination, otherwise crop yield loss can occur (Almeida et al. 2024; Lacey et al. 2023; Qin et al. 2021; Roth et al. 2023). Across different CC types, grass CCs provided a season-long (>8 WAP) reduction in ASWD and ASWB. Legume CCs provided only early-season ASW suppression; however, legume CCs can offer other benefits such as fixing atmospheric nitrogen (Thapa et al. 2018b; White et al. 2022). CC residues remaining on the soil surface were more effective at suppressing ASWD than incorporated residues. Moreover, mechanical, chemical, and integrated termination methods showed similar ASW suppression, allowing growers to choose based on their CC termination efficiency. When compared with NCC, CCs did not reduce ASWD and ASWB if herbicides were used for in-season weed management. This finding does not imply CCs do not provide ASW suppression. CCs can reduce the number of ASW plants exposed to herbicides, thereby reducing selection pressure for the evolution of herbicide resistance among ASW (Hand et al. 2021). However, CCs alone are not effective to provide AQ36 season-long ASW suppression, and therefore herbicides should be included with CCs for effective ASW management (Burgos and Talbert 1996a; Dearden 2022; Norsworthy et al. 2016). Overall, CCs were found to be effective for the suppression of ASW and can be integrated with other management tools.

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