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Short title: Cover crop for pigweed control

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

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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 to no CC (NCC) in temperate regions including US and Canada. We found 41 studies conducted across US and Canada and extracted 595 paired observations. The results indicate that CCs reduced the ASWD by 58% in the early- [0–4 weeks after crop planting (WAP)], by 48% in the mid- (5–8 WAP) and by 44% in the late- (>8 WAP) season. 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 weeks of crop planting reduced ASWD by ≥50%. Cover crop 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-, 53% and 59% in mid-, 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. Cover crop residues remaining on the soil surface were more effective for reducing ASWD than incorporation. Cover crops did not affect ASWD or ASWB compared to NCC when herbicides were used for in-season weed management. In general, CCs were found to reduce ASWD, and ASWB, therefore can be used as an effective tool for integrated management of *Amaranthus* spp.

Keywords: *Amaranthus* spp. weed biomass and density; integrated weed management; Palmer amaranth; redroot pigweed; smooth pigweed; waterhemp.

Introduction

Amaranthus is a genetically diverse plant genus with about 75 species (Ward et al., 2013), distributed across six out of the seven 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 US 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 US and Canada (Van Wychen 2020; Van Wychen 2022), whereas *A. tuberculatus* was reported as the second most troublesome weed in corn and soybean (Van Wychen 2020; Van Wychen 2022).

Genetic diversity, phenotypic plasticity, rapid growth rate, and 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 six weeks 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 one hectare 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; 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 US 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 susceptible weeds in crop production systems (Bunchek et al. 2020; Kumar et al. 2020; Kumari et al. 2023a, 2023b). Cover crops 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 two-year study in Arkansas, US, 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 to no CC (NCC). In a four-year study in Missouri, US, 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 two-year multilocation study in US, 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, US, 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 four weeks after planting (WAP) cotton compared to a 44% reduction at eight WAP (Palhano et al. 2017). Similarly, in a Pennsylvania study, Curran et al. (1994) found that hairy vetch (*Vicia villosa* Roth) decreased *A. hybridus* density by 76% at four WAP corn compared to no reduction at eight 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 been done to evaluate 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; Osipitan et al. 2019). Meta-analysis studies have evaluated the role of CCs for suppressing weeds (Dong and Zeng 2024; Nichols et al. 2020; Osipitan et al. 2018; Osipitan et al. 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, 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 to 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.) H.S. Irwin & Barneby]. Therefore, it was required to evaluate the effect of CCs on suppression of specific problematic weed species. 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 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 (0–4 WAP), mid (5–8 WAP), and late (>8 WAP) crop growth stages in the growing season compared to no CC (NCC) in temperate regions including US and Canada.

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Materials and Methods

Literature Search and Data Extraction

Literature was searched 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: (i) be conducted in the US or Canada, (ii) include a NCC treatment for comparison (iii) report data on at least one of the four *Amaranthus* spp, viz. *A. palmeri*, *A. retroflexus*, *A. hybridus*, and *A. tuberculatus*, and (iv) report at least one of the response variable (i.e., weed biomass and/or weed density) for both CC treatment and NCC control groups. Only studies conducted in the US and Canada were included in this meta-analysis, as the above mentioned ASW are problematic in these two temperature 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 following data were extracted from these papers:

- *Experiment 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.
- *Weed data*: common name, scientific name, weed data collection time (weeks after crop planting; WAP), mean density and/or biomass for CC and NCC groups.

Meta-analysis: Overall Effect of Cover Crops on Suppression of Amaranthus spp. Weed density, and Amaranthus spp. Weed Biomass

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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).

$$ln\ (RR) = \ln(X_t/X_c) \qquad [1]$$

where '$ln(RR)$' 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 a 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 i.e. 0.1 (n = 47; for the studies which reported mean values as decimals) or 1 (n = 31; for the studies which 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, sensitivity analysis was performed with and without the inclusion of imputed values, indicating 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, standard error (SE), or standard deviation (SD). Therefore, the standard variance approach of Hedges and Olkin (2014) cannot be used for weighing the individual effect sizes. As proposed by Adams et al. (1997), experimental replications were used to weight the individual effect sizes (Equation 2):

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

where 'w_i' is the weight of individual effect size for i^{th} observation, 'N_t' and 'N_c' are the number of replications for the CC and NCC groups, respectively. Multiple effect sizes were calculated from studies reporting results from multi-year or multi-location experiments, and/or examining more than one CC treatments sharing the same NCC control group. This approach could lead to dependency between effect sizes within and across studies. Therefore, a multi-level mixed effects meta-analytic model was designed using the *nlme* package in R (Pinheiro et al. 2023; Singh et al.

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2022; Singh et al. 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 Cover Crop 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 species*: *A. palmeri*/*A. hybridus*/*A. retroflecxus*/*A. tuberculatus*/mixed (mixed population of two or more earlier 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 [*Glycine max* (L.) Merrill]}/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).
- *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 multi-level 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; Singh et al. 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 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 weighing factor. Cover crop biomass required for 50% ASWD and ASWB reduction were 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 (i.e., weights assigned for individual ln*RR*). Furthermore, random effects were subtracted from individual effect sizes before creating bubble plots (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; Singh et al. 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, followed by re-running the primary multi-level mixed effects meta-analysis model each time to recalculate the overall effect sizes without the inclusion of that specific study.

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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 US (one each from Iowa, North Carolina, and Pennsylvania; two each from Missouri and Tennessee; three each from Alabama, Illinois, Kansas, Michigan, Mississippi, 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 cep*a L.), pumpkin (*Cucurbita pepo* L.), southern pea [*Vigna unguiculata* (L.) Walp.], sweet potato [*Ipomoea batatas* (L.) Lam.], and tomato]. One study (Wortman 2012) included three crops i.e., 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).

Amaranthus spp. weed data were reported in 23 studies for early (0–4 WAP) 23 for mid (5–8 WAP), and 21 for late (>8 WAP) season (Table 1). Most studies evaluated *A. palmeri* (n =24) followed by *A. retroflexus* (n =8), *A. tuberculatus* (n = 6), and *A. hybridus* (n =3), and mixed (n = 4). Out of the 41 articles, one 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 (Walter and Young 2010; Wang 2008), and broadcasting fb incorporation (Nqouajio 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).

Cover crops 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 winter-kill in two 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. Cover crop residues were standing in 28 studies, rolled (lying on the soil surface) in 16, and soil incorporated in six studies (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, six used herbicides, and one 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 Cover Crops on Amaranthus spp. Weed Density and Amaranthus spp. Weed Biomass

Cover crops reduced ASWD by 58% (95% CI = –69 % to –43%) in the early- (0–4 WAP), by 48% (95% CI = –63 % to –26%) in the mid- (5–8 WAP), and by 44% (95% CI = –57 % to –27%) in the late-season (> 8 WAP) compared to NCC, (Figure 2). Germination of AWS seed is light-dependent, meaning that both the presence and light quality influence their ability to germinate (Gallagher and Cardina 1998; Jha et al. 2010). *Amaranthus* spp. weed 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 AWS germination, with higher seed germination under red light than far-red (Gallagher and Cardina 1998; Jha et al. 2010). Cover crop residues act as a physical barrier blocking sunlight reaching the soil surface and also decreases the ratio of red:far-red light, thereby reduction the germination and density of AWS (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 AWS (Jha et al. 2010; Steckel et al. 2004). In a study conducted in Illinois, US, Steckel et al. (2004) found that AWS germination increased by 5% when the temperature was raised from 20^{o}C to 25^{o}C, and by 17% when the temperature was further increased to 30^{o}C. Similarly, AWS germination increased by 15% by alternating the temperature ±40% of constant temperature in a sinusoidal fashion (Steckel et al. 2004). Cover crop residues have a shading effect and enhance soil moisture content which can lower daytime surface soil temperature from an average of 2^{o}C (Blanco-Canqui 2020) to as much as 6^{o}C (Wagner-Riddle et al. 1994). Cover crop residues can also decrease the diurnal fluctuations in the soil surface temperature (Blanco-Canqui 2020; Teasdale and Mohler 1993).

Cover crops reduced ASWB by 59% (95% CI = –78 % to –24%) in the early-, by 55% (95% CI = –72 % to –27%) in the mid-, and 37% (95% CI = –52 % to –16%) in the late-season (Figure 2). Cover crops reduce AWS germination, which means less AWS plants ha^{-1} 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 days of termination), and late-season (over 50 days of 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 compared to 59% reduction in ASWB in this meta-analysis. This might be because the 'early-season' has been defined as 0–4 WAP in this study compared to an earlier time of 'at CC termination' by Dong and Zeng (2024).

Effect of Cover Crop Biomass, and Time Interval between Cover Crop Termination and Subsequent Crop Planting on Amaranthus spp. Weed Density and Amaranthus spp. Weed Biomass

The regression analysis showed that CC biomass has a significant effect on the ASWD and ASWB (Figure3). A linear regression model was the best fit for ASWD and ASWB (Table 2). Cover crop biomass of 4,079 kg ha^{-1} was required to reduce the ASWD by 50% (Figure3). 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 AS, 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.), pitted morningglory, prickly sida, yellow nutsedge (*Cyperus esculentus* L.) which had large sized-high mass seeds compared to ASW. It has been reported that weed emergence sensitivity to CC residue is inversely related to their 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 to NCC, whereas no significant effect of CC on fall panicum, and yellow nutsedge density. Similarly, in Mississippi, Reddy (2003) reported 37% reduction in *A. hybridus* density with cereal rye CC, whereas 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 their 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% (Figure3). 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 Nicholas et al. (2020) included studies from the midwestern US compared to our meta-analysis which have a significant number of studies from the southeast US (Table 1). Rapid accumulation of heat units and high annual rainfall in the southeast US 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 southeast US (Weisberger et al. 2023). Secondly, ASW has higher biomass accumulation rate compared to 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 has been included in meta-analysis by Nicholas et al. (2020) along with ASW. Therefore, higher CC biomass may be needed for ASWB suppression than their emergence/density suppression.

Cover crops normally do not produce 4,000–5,000 kg ha^{-1}, except for warm-humid (>7 USDA plant hardiness zone and > 750 mm annual precipitation), and warm-semi-arid (>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-semi-arid 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 zone 5–7 and > 750 mm annual precipitation) and cold-humid (USDA plant hardiness zone <5 and > 750 mm annual precipitation) regions (Nichols 2020; Ruis et al. 2019). Cover crops can be planted early by interseeding in standing crops in the fall season (Caswell 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 to planting in the last week of September, and 56% more biomass compared to planting in mid-October. Similarly, in a Nebraska study, Carmona et al. (2022) reported 316% increase in cereal rye + oat (*Avena sativa* L.) CC mixture biomass at termination with mid-September planting compared to 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 weeks of crop planting to reduce the ASWD by 50% or more (Figure4). This might be because delaying CC termination close to crop planting time allows CCs to accumulate more biomass. In a study conducted in Virginia, Kumar et al. (2023b) found 139% increase in rapeseed or canola (*Brassica napus* L.) CC biomass when terminated at corn planting compared to terminating four weeks 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 to terminating two weeks before planting. Adoption of "planting green" practice where CCs are terminated at or some time 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%–76% reduction in corn yield when cereal rye termination was delayed by three weeks, but no negative effect on corn yield with delayed hairy vetch termination. In a Pennsylvania study, Reed et al. (2019) found 5%–10% reduction in corn yield with four weeks delay in cereal rye termination. Liebl et al. (1992) reported 21% reduction in soybean yield with delaying cereal rye termination by two weeks in Illinois. However, neutral (Duiker and Curran 2005; Reed et al. 2019; Denton et al. 2023) and positive effect (Marcillo and Miguez 2017; Overmyer et al. 2023) of delayed CC termination on crop yield has also been reported.

Effect of Cover Crops 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, temperature and light requirement for germination (Gallagher and Cardina 1998; Jha et al. 2010; Steckel et al. 2004). Cover crops decreased *A. palmeri* density by 59% (99% CI = –76% to –29%) in the early-, 50% (99% CI = –74% to –1%) in the mid-, and 45% (99% CI = –64% to –15%) in the late-season compared to NCC (Figure 5). Cover crops reduced redroot density by 75% (99% CI = –76% to –29%) in the early-season, but 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 studies and observations 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 to 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 to 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 Amaranthus spp. Weed Density and Amaranthus spp. Weed Biomass Suppression by Cover Crops

Cover crops did not reduce ASWB in cotton and soybean in late-season, and there was not enough data observation for other crops. Cover crops 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 to NCC. Cover crops also decreased ASWD in vegetable crops by 92% (99% CI = –98% to –66%) in the early-season, whereas 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 mid-season (0.026) at the 95% CI level; however, these effects were not significant at the 99% CI. 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

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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 et al. 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-, 48% (99% CI = –67% to –17%) in the mid-, and 52% (99% CI = –70 % to –21%) in the late-season compared to NCC (Figure 5). The effect of CCs on ASWD was not significant (CI = 99%) when herbicides were used for in-season weed management (p value of 0.45, 0.06, and 0.02 for early-, mid-, 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 mixture reduced the number of *A. hybridus*s exposed to postemergence herbicide by approximately 50% and 30% compared to NCC, respectively. Moreover, sole reliance on CCs for season-long ASW management is not recommended because CCs are not able to provide complete AS control and seed production by uncontrolled ASW can increase the ASW infestation in the upcoming years (Dearden Jr. 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 to 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 mechanically weeded treatment, but not in herbicide treatment. This might be because mostly residual herbicides are used for early-season weed control that does not allow ASW to germinate for a certain period. Whereas mechanical weeding manages only the emerged ASW plants and do not have residual activity, so the ASW emerged 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 mid-season (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 preemergencefb postemergence herbicide treatment in the late-season, it was not significant (p value = 0.11; 99% CI = –67% to 27%) compared to NCC. Whereas CCs reduced ASWD by 59% (99% CI = –81% to –8%) in postemergence-only treatment compared to NCC in late-season. This might be because ASW have a long window of emergence (Franca 2015) and most of the postemergence herbicides were used in early to mid-season 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 program have soil residual activity and do not allow weeds to germinate and mask the effect of CCs (Norsworthy et al. 2016). In Arkansas, Northworthy et al. (2016) found that compared to NCC, cereal rye CCs reduced ASWD by 44% in postemergence only treatment in late-season (19–24 WAP), but no effect of CCs in preemergence fb postemergence herbicide program. Similarly, in a study conducted in Iowa, Dearden Jr. (2022) reported 41% decrease in late-season (10 WAP) ASWD with cereal rye CC in postemergence only treatment compared to NCC, whereas decrease in ASWD was 27% for 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 Cover Crop Type and Planting Method on Amaranthus spp Weed Density and Amaranthus spp Weed Biomass

Grass CCs decreased ASWD by 60% (99% CI = –73% to –41%) in the early-, 53% (99% CI = –71% to –23%) in the mid-, and 44% (99% CI = –61% to –20%) in the late-season compared to NCC (Figure 5). Similarly, the CC mixture reduced ASWD by 77% (99% CI = –88% to –55%) in the early-, 59% (99% CI = –80% to –17%) in the mid-, and 47% (99% CI = –68% to –14%) in the late-season (Figure 5). The mixtures had statistically similar ASWD reduction compared to 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 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). Cover crop residue with C:N ratio of 9:1 to 16:1 suppressed *A. retroflexus* by 50% in early-season (2–4 WAP), whereas C:N ratio of >20:1 was required for 50% suppression of *A. retroflexus* in mid-season (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 was not enough data to evaluate the effect of brassica CCs on mid-season 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 and 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 2008). In addition, Wang (2008) recorded ASWD data for the late-season (8–10 WAP) when the weed suppression 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 the early and mid-season, 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 to ASWD (Figure 3). Cover crop residue decomposes with time (Adhikari et al. 2024; Thapa et al. 2022), resulting in less biomass available for ASWB suppression during 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 broadcasting fb incorporation method. This might be because drill-planted CCs germinate early and have better stand establishment compared to broadcasting fb incorporation (Brennan and Leap 2014; Noland et al. 2018). In a study conducted in California, Brennan and Leap (2014) found that broadcast fb incorporation had 33%–50% lower CC stand compared to drill planting at two weeks 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 either of early, mid, or late-season was not evaluated due to the limited number of observations.

Effect of Cover Crop Termination Method and Residue Fate on Amaranthus spp. Weed Density and Amaranthus spp. Weed Biomass

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%–64% in the early-, by 39%–63% in the mid-, and by 39%–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 mid-season, respectively. There were not sufficient observations to evaluate the winter-kill 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, cover crop 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 to chemical termination. Similarly, in a multi-state study, Masiunas et al. (1995) found 12% lower tomato yield in mowed cereal rye plots compared to herbicide terminated plots. Therefore, the termination method should be selected based on efficacy of CC termination.

The data were limited to evaluate the fate of CC residue on ASWB. Cover crop 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 2–5 weeks 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 to NCC. *Amaranthus* spp. weed density 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, by late-season allelochemicals either leach down with rain/irrigation water or undergo decomposition becoming ineffective for weed suppression (An et al. 2002; Rice et al. 2012; Teasdale et al. 2012). In a study conducted in Maryland, Teasdale et al. (2012) found that cereal rye incorporated in soil inhibited *A. hybridus* germination for two weeks after incorporation, which coincided period 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 showed that the individual effect sizes followed a normal symmetrical distribution, which is indicative of a no publication bias. In all cases, the peak of the kernel density plots centered towards a slightly negative response ratio values indicating that the CCs exhibit weed suppression ability for *Amaranthus* spp. throughout the subsequent crop season. Moreover, sensitivity analysis performed using the *Jacknife* procedure showed that no single study appeared to have influential effect on the mean effect sizes (Fig. 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 targeted ones.

- 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 CCs 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.
- Cover crop biomass C:N ratio at termination affects decomposition rate (Adhikari et al. 2024; Thapa et al. 2022) and thereby have 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 selected 41 articles, the CCs were terminated at different growth stages–resulting in different C:N ratio. The selected articles, however, did not provide information on C:N ratio of CC biomass at termination, thereby we were not able to 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 the 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 Werd 2023; Marcillo and Miguez 2017; Peng et al. 2024). Therefore, the inclusion of crop yield from a smaller subset of CC studies included in this meta-analysis (n = 41) would not have given a robust conclusion.
- 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; PRE fb postemergence herbicide application timing, and legume CC for late-season) which limited ability to estimate conclusive effect size for these sub-groups.

- The most studies included in this meta-analysis did not report measures of within-study variation such as coefficient of variance, standard deviation 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 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 the ASWD by 58%, 48%, and 44%, and ASWB by 59%, 55%, and 37% in early, mid, and late-season, respectively, compared to NCC. *Amaranthus* spp. weed density and ASWB suppression were found to be directly related to the amount of CC biomass accumulation. Cover crop 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 (>4,000–5,000 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; Roth et al. 2023; Qin et al. 2021). 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 (White et al. 2022; Thapa et al. 2018). Cover crop residues remaining on the soil surface were more effective at suppressing AWSD than their incorporation. Moreover, mechanical, chemical, and integrated termination methods showed similar AWS suppression, allowing growers to choose based on their CC termination efficiency. When compared to 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. Cover crops 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, sole CC are not effective to provide season

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long AS suppression and therefore herbicides should be included with CCs for effective ASW management (Burgos and Talbert 1996a; Dearden Jr. 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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References

Acharya J, Bakker MG, Moorman TB, Kaspar TC, Lenseen AW, Robertson AE (2017) Time interval between cover crop termination and planting influences corn seedling disease, plant growth and yield. Plant Dis 101:591–600

Acharya J, Moorman TB, Kaspar TC, Lenseen AW, Robertson AE (2020) Cover crop rotation effects on growth and development, seedling disease, and yield of corn and soybean. Plant Dis 104:677–687

Acharya J, Moorman TB, Kaspar TC, Lenseen AW, Gailans S, Robertson AE (2022) Effect of planting into a green cereal rye cover crop on growth and development, seedling disease and yield of corn. Plant Dis 106:114–120

Adams DC, Gurevitch J, Rosenberg MS (1997) Resampling tests for meta-analysis of ecological data. Ecology 78:1277–1283

Adhikari AD, Shrestha P, Ghimire R, Liu Z, Pollock DA, Acharya P, Aryal DR (2024) Cover crop residue quality regulates litter decomposition dynamics and soil carbon mineralization kinetics in semi-arid cropping systems. Appl Soil Ecol 193:105160

Almeida TF, Robinson E, Matthiesen-Anderson R, Robertson AE, Basche A. 2024. Effect of cover crop species and termination timing on corn growth and seedling disease. Agron J 116:1792–1803

An M, Johnson IR, Lovett JV (2002) Mathematical modelling of residue allelopathy: the effects of intrinsic and extrinsic factors. Plant Soil 246:11–22

Anderson M (2023) A new Palmer amaranth find underscores importance of scouting. Integrated crop management, Iowa State University Extension and Outreach.

Assad R, Reshi ZA, Jan S, Rashid I (2017) Biology of Amaranths. Bot Rev 83:382–436

Aulakh JS, Price AJ, Enloe SF, Santen EV, Wehtje G, Patterson MG (2012) Integrated Palmer amaranth management in glufosinate–resistant cotton: I. Soil–inversion, high–residue cover crops and herbicide regimes. Agron 2:295–311

Aulakh JS, Price AJ, Enloe SF, Santen EV, Wehtje G, Patterson MG (2013) Integrated Palmer amaranth management in glufosinate–resistant cotton: II. Primary, secondary and conservation tillage. Agron 3:28–42

Basche A, DeLonge M (2017) The impact of continuous living cover on soil hydrologic properties: a meta-analysis. Soil Sci Soc Am J 81:1179–1190

Beckie HJ (2020) Herbicide resistance in plants. Plants 9:435

Bensch CN, Horak MJ, Peterson D (2003) Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci 51:37–43

Bish M, Dintelmann B, Oseland E, Vaughn J, Bradley K (2021) Effects of cereal rye seeding rate on waterhemp (*Amaranthus tuberculatus*) emergence and soybean growth and yield. Weed Technol 35: 838–844

Blanco-Canqui H, Ruis SJ (2020) Cover crop impacts on soil physical properties: A review. Soil Sci Soc Am J 84:1527–1576

Brennan EB, Leap JE (2014) A comparison of drill and broadcast methods for establishing cover crops on beds. HortSci 49:441–447

Bunchek JM, Wallace JM, Curran WS, Mortensen DA, VanGessel MJ, Scott BA (2020) Alternative performance targets for integrating cover crops as a proactive herbicide-resistance management tool. Weed Sci 68:534–544

Burgos NR, Talbert RE (1996a) Weed control and sweet corn (*Zea mays* var. *rugosa*) response in a no–till system with cover crops. Weed Sci 44:355–361

Burgos NR, Talbert RE (1996b) Weed control by spring cover crops and imazethapyr in no–till southern pea (*Vigna unguiculata*). Weed Technol 10:893–899

Carmona GI, Robinson E, Rosa AT, Proctor CA, McMechan AJ (2022) Impact of cover crop planting and termination dates on arthropod activity in the following corn. J Econ Entomol 115:1177–1190

Carrera LM, Abdul-Baki AA, Teasdale JR (2004) Cover crop management and weed suppression in no-tillage sweet corn production. HortSci 39:1262–1266

Carvalho SJP de, Christoffoleti P (2006) Influence of light and temperature on germination of five weed species of the *Amaranthus* genus. Bragantia 66:527–533

Caswell K, Wallace JM, Curran WS, Mirsky SB, Ryan MR (2019) Cover crop species and cultivars for drill-interseeding in Mid-Atlantic corn and soybean. Agron J 111:1060–1067

Chahal I, Van Eerd LL (2023) Do cover crops increase subsequent crop yield in temperate climates? A meta-analysis. Sustainability 15:6517

Cornelius CD, Bradley KW (2017) Influence of various cover crop species on winter and summer annual weed emergence in soybean. Weed Technol 31:503–513

Crawford LE, Williams MM, Wortman SE (2018) An early–killed rye (*Secale cereale*) cover crop has potential for weed management in edamame (*Glycine max*). Weed Sci 66:502–507

Curran WS, Hoffman LD, Werner EL (1994) The influence of a hairy vetch (*Vicia villosa*) cover crop on weed control and corn (*Zea mays*) growth and yield. Weed Technol 8:777–784

Curran WS, Hoover RJ, Mirsky SB, Roth GW, Ryan MR, Ackroyd VJ, Wallace JM, Dempsey MA, Pelzer C J (2018) Evaluation of cover crops drill interseeded into corn across the Mid-Atlantic region. Agron J 110:435–443

Currie RS, Klocke NL (2005) Impact of a terminated wheat cover crop in irrigated corn on atrazine rates and water use efficiency. Weed Sci 53:709–716

Davis AS (2010) Cover–crop roller–crimper contributes to weed management in no–till soybean. Weed Sci 58:300–309

Dearden Jr ES (2022) Utilizing a cereal rye cover crop to manage herbicide–resistant horseweed (*Erigeron canadensis*) and waterhemp (*Amaranthus tuberculatus*) in soybean production systems. Master's thesis. Ames, IA: Iowa State University. 53 p

den Hollander NG, Bastiaans L, Kropff MJ (2007) Clover as a cover crop for weed suppression in an intercropping design: II. Competitive ability of several clover species. Eur J Agron 26:104–112

Denton S, Raper T, Stewart S, Dodds D (2023) Cover crop termination timings and methods effect on cotton (*Gossypium hirsutum* L.) development and yield. Crop, Forage & Turf Manag 9(1):e20206

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of deep tillage and a rye cover crop on glyphosate–resistant Palmer amaranth (*Amaranthus palmeri*) emergence in cotton. Weed Technol 26:832–838

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of deep tillage, a rye cover crop, and various soybean production systems on Palmer amaranth emergence in soybean. Weed Technol 27:263–270

Dong F, Zeng W (2024) Effects of fall and winter cover crops on weed suppression in the United States: A meta-analysis. Sustainability16:3192

Duiker SW, Curran WS (2005) Rye cover crop management for corn production in the northern mid-Atlantic region. Agron J 97:1413–1418

Fast BJ, Murdock SW, Farris RL, Wills JB, Murray DS (2009) Critical timing of Palmer Amaranth (*Amaranthus palmeri*) removal in second-generation glyphosate-resistant cotton. J Cotton Sci 13:32–36

Ficks TS, Lowry CJ, Wallace JM (2022) Weed seed mass affects seedling establishment and resource allocation patterns across a cereal rye surface residue gradient. Weed Res 69: 49–58

Franca LX (2015) Emergence patterns of common waterhemp and Palmer amaranth in southern Illinois. Master's thesis. Carbondale: Southern Illinois University. 126 p

Gallagher RS, Cardina J (1998) Phytochrome-mediated *Amaranthus* germination I: Effect of seed burial and germination temperature. Weed Sci 46:48–52

Grint KR, Arneson NJ, Oliveira MC, Smith DH, Werle R (2022) Cereal rye cover crop terminated at crop planting reduces early-season weed density and biomass in Wisconsin corn–soybean production. Agrosyst Geosci Environ 5:e20245

Hand LC, Nichols RL, Webster TM, Culpepper AS (2019) Cereal rye cover crop and herbicide application method affect cotton stand, Palmer amaranth (*Amaranthus palmeri*) control, and cotton yield. Weed Technol 33:794–799

Hand LC, Randell TM, Nichols RL, Steckel LE, Basinger NT, Culpepper AS (2021) Cover crops and residual herbicides reduce selection pressure for Palmer amaranth resistance to dicamba–applied postemergence in cotton. Agron J 113:5373–5382

Hay MM, Dille JA, Peterson DE (2019) Integrated pigweed (*Amaranthus* spp.) management in glufosinate–resistant soybean with a cover crop, narrow row widths, row–crop cultivation, and herbicide program. Weed Technol 33:710–719

Heap I (2024) The international survey of herbicide resistant weeds. Available Online at: http://www.weedscience.org Accessed: July 05, 2024

Hedges LV, Gurevitch J, Curtis PS (1999) The meta-analysis of response ratios in experimental ecology. Ecology 80:1150–1156

Hedges LV, Olkin I (2014) Statistical Methods for Meta-analysis. Orlando, FL: Academic Press. 369 p

Horak MJ, Loughin TM (2000) Growth analysis of four *Amaranthus* species. Weed Sci 48:347–355

Jianyang L, Davis AS, Tranel PJ. (2012) Pollen biology and dispersal dynamics in waterhemp (*Amaranthus tuberculatus*). Weed Sci 60:416–422

Jha P, Norsworthy JK, Riley MB, Bridges W (2010) Annual changes in temperature and light requirements for germination of Palmer amaranth (*Amaranthus palmeri*) seeds retrieved from soil. Weed Sci 58:426–432

Jhala AJ, Norsworthy JK, Ganie ZA, Sosnoskie LM, Beckie HJ, Mallory-Smith CA, Liu J, Wei W, Wang J, Stoltenberg DE (2021) Pollen-mediated gene flow and transfer of resistance alleles from herbicide-resistant broadleaf weeds. Weed Technol 35:173–187

Kambach S, Bruelheide H, Gerstner K, Gurevitch J, Beckmann M, Seppelt R (2020) Consequences of multiple imputation of missing standard deviations and sample sizes in meta-analysis. Ecol Evol 10:11699–11712

https://doi.org/10.1017/wsc.2024.99 Published online by Cambridge University Press

Koger CH, Reddy KN (2005) Effects of hairy vetch (*Vicia villosa*) cover crop and banded herbicides on weeds, grain yield, and economic returns in corn (*Zea mays*). J Sustain Agr 26:107–124

Koger CH, Reddy KN, Shaw DR (2002) Effects of rye cover crop residue and herbicides on weed control in narrow and wide row soybean planting systems. Weed Biol Manag 2:216–224

Kumar V, Obour A, Liu R, Stahlman PW, Jha P, Manuchehri MR, Dille JA, Holman J (2020) Integrating cover crops for weed management in the semiarid U.S. Great Plains: Opportunities and challenges. Weed Sci 68:311–323

Kumar V, Singh M, Kaur R, and Jhala AJ (2023a) The scenario of herbicide-resistant weeds: Management challenges and perspectives. IJWS 55:123-132

Kumar V, Singh V, Flessner M, Reiter MS, Kuhar T, Mirsky S (2023b) Volunteer rapeseed infestation and management in corn. Agron J 115:2925–2937

Kumari A, Price AJ, Gamble A, Li S, Jacobson A (2024) Integrating cover crops and herbicides for weed control in soybean. Weed Technol 38:e73

Kumari A, Price AJ, Korres NE, Gamble A, Li S (2023a) Effect of crimson clover on the critical period of weed control in conservation tillage corn. Front Agron 4:1068365

Kumari A, Price AJ, Korres NE, Gamble A, Li S (2023b) Influence of a cereal rye cover crop on the critical period for weed control in soybean. Weed Technol 37:25–33

Lacey C, Camberato J, Armstrong S (2023) Field based ^{15}N study: an investigation of cereal rye N fate and utilization by the subsequent corn and soybean. Nutr Cycl Agroecosys 125: 205–217

Legleiter T, Johnson B (2013) Palmer amaranth biology, identification, and management. Purdue Extension, WS-51, 13 p

Liebl R, Simmons F, Wax L, Stoller E (1992) Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol 6:838–846

Liebman M, Sundberg DN (2006) Seed mass affects the susceptibility of weed and crop species to phytotoxins extracted from red clover shoots. Weed Sci 54:340–345

Loux MM, Dobbels AF, Bradley KW, Johnson WG, Young BG, Spaunhorst DJ, Steckel LE (2017) Influence of cover crops on management of *Amaranthus* species in glyphosate– and glufosinate–resistant soybean. Weed Technol 31:487–495

https://doi.org/10.1017/wsc.2024.99 Published online by Cambridge University Press

Marcillo GS, Miguez FE (2017) Corn yield response to winter cover crops: An updated meta analysis. J Soil and Water Conserv 72:226–239

Masiunas JB, Weston LA, Weller SC (1995) The impact of rye cover crops on weed populations in a tomato cropping system. Weed Sci 43:318–323

Massinga RA, Currie RS, Horak MJ, Boyer J (2001) Interference of Palmer amaranth in corn. Weed Sci 49:202–208

McCall CM (2018) Integrating cover crops and herbicides for horseweed and Palmer amaranth management in no–till soybean. Master's thesis. Manhattan, KS: Kansas State University. 134 p

Miranda JWA, Jhala AJ, Bradshaw J, Lawrence NC (2021) Palmer amaranth (*Amaranthus palmeri*) interference and seed production in dry edible bean. Weed Technol 35: 995–1006

Mirsky SB, Curran WS, Mortenseny DM, Ryany MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380–389

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene C. L, Moyer JW (2017) Overcoming weed management challenges in cover crop–based organic rotational no-till soybean production in the eastern United States. Weed Technol 27:193–203

Moore JW, Murray DS, Westerman RB (2004) Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum bicolor*). Weed Technol 18:23–29

Moore MJ, Gillespie TJ, Swanton CJ (1994) Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol 8:512–518

Nakagawa S, Noble DW, Lagisz M, Spake R, Viechtbauer W, Senior AM (2023) A robust and readily implementable method for the meta-analysis of response ratios with and without missing standard deviations. Ecol Lett 26:232–244

Ngouajio M, Mennan H (2005) Weed populations and pickling cucumber (*Cucumis sativus*) yield under summer and winter cover crop systems. Crop Prot 24:521–526

Nichols V, Martinez-Feria R, Weisberger D, Carlson S, BassoB, Basche A (2020) Cover crops and weed suppression inthe U.S. Midwest: A meta-analysis and modeling study. Agricul Environ Lett 5:e20022

Noland RL, Wells MS, Sheaffer CC, Baker JM, Martinson KL, Coulter JA (2018) Establishment and function of cover crops interseeded into corn. Crop Sci 58:863–873

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating herbicide programs with harvest weed seed control and other fall management practices for the control of glyphosate–resistant Palmer amaranth (*Amaranthus palmeri*). Weed Sci 64:540–550

Nunes J, Arneson NJ, Wallace J, Gage K, Miller E, Lancaster S, Werle R (2023) Impact of cereal rye cover crop on the fate of preemergence herbicides flumioxazin and pyroxasulfone and control of *Amaranthus* spp. in soybean. Weed Sci 71:493–505

Osipitan OA, Dille JA, Assefa Y, Knezevic SZ (2018) Cover crop for early-season weed suppression in crops: Sys-tematic review and meta-analysis. Agron J 110:2211–2221

Osipitan OA, Dille JA, Assefa Y, Radicetti E, Ayeni A, Knezevic SZ (2019) Impact of cover crop management on level of weed suppression: A Meta-Analysis. Crop Sci 59:833–842

Otte B, Mirsky S, Schomberg H, Davis B, Tully K (2019) Effect of cover crop termination timing on pools and fluxes of inorganic nitrogen in no-till corn. Agron J 111:2832–2842

Overmyer K, Looker W, Dorrance AE, Tilmon KJ, Lindsey LE (2023) Influence of rye/oat cover crop in a two-year soybean production system. Agron J 115:303–313

Oys EA (2022) Winter cover crop impacts on weed dynamics in eastern and central Nebraska. Master’s thesis. Lincoln, IA: University of Nebraska-Lincoln. 113 p

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 372:n71

Palhano MG, Norsworthy JK, Barber T (2017) Cover crops suppression of Palmer amaranth (*Amaranthus palmeri*) in cotton. Weed Technol 32:60–65

Peng Y, Wang L, Jacinthe PA, Ren W (2024) Global synthesis of cover crop impacts on main crop yield. Field Crop Res 310:109343

Philibert A, Loyce C, Makowski D (2012) Assessment of the quality of meta-analysis in agronomy. Agric Ecosyst Environ 148:72–82

Pinheiro J, Bates D, DebRoy S, Sarkar D, Heisterkamp S, Willigen BV, Ranke J (2023) NLME: Linear and Nonlinear Mixed Effects Models. https://cran.rproject.org/web/packages/nlme/nlme.pdf. Accessed: June 10, 2024

Pittman KB, Barney JN, Flessner ML (2020) Cover crop residue components and their effect on summer annual weed suppression in corn and soybean. Weed Sci 68:301–310

Price AJ, Balkcom KS, Duzy LM, Kelton JA (2012) Herbicide and cover crop residue integration for *Amaranthus* control in conservation agriculture cotton and implications for resistance management. Weed Technol 26:490–498

Price AJ, Monks CD, Culpepper AS, Duzy LM, Kelton JA, Marshall MW, Nichols RL (2016) High–residue cover crops alone or with strategic tillage to manage glyphosate–resistant Palmer amaranth (*Amaranthus palmeri*) in southeastern cotton (*Gossypium hirsutum*). J Soil Water Conserv 71:1–11

Pustejovsky J (2022) clubSandwich: Cluster-robust (sandwich) variance estimators with small-sample corrections. https://cran.rproject.org/web/packages/clubSandwich/clubSandwich.pdf. Accessed: June 10, 2023. Accessed: August 11, 2024

Qin Z, Guan K, Zhou W, Peng B, Villamil MB, Jin Z, Tang J, Grant R, Gentry L, Margrnot A J, Bollero G, Li Z (2021) Assessing the impacts of cover crops on maize and soybean yield in the U.S. Midwestern agroecosystems. Field Crop Res 273:108264

R Core Team (2021). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.Rproject.org/. Accessed: August 11, 2024

Reddy KN (2003) Impact of rye cover crop and herbicides on weeds, yield, and net return in narrow-row transgenic and conventional soybean (*Glycine max*). Weed Technol 17:28–35

Reed HK, Karsten HD, Curran WS, Tooker JF, Duiker SW (2019) Planting green effects on corn and soybean production. Agron J 111:2314–2325

Reinhardt Piskackova TA, Reberg-Horton SC, Richardson RJ, Jennings KM, Franca L, Young BG, Leon RG (2021) Windows of action for controlling Palmer amaranth (*Amaranthus palmeri*) using emergence and phenology models. Weed Res 61:188–198

Rice CP, Cai G, Teasdale JR (2012) Concentrations and allelopathic effects of benzoxazinoid compounds in soil treated with rye (*Secale cereale*) cover crop. J Agri Food Chem 60:4471–4479

Rogers KM (2017) Integrating a cereal rye cover crop and soybean row width with herbicides to manage Palmer amaranth in Michigan. Master's thesis. East Lansing, MI: Michigan State University. 80 p

Rosario-Lebron, A, Leslie AW, Yurchak VL, Chen G, Hooks CRR (2019) Can winter cover crop termination practices impact weed suppression, soil moisture, and yield in no-till soybean [*Glycine max* (L.) Merr.]? Crop Prot 116:132–141

Roth RT, Lacey CG, Camberato JJ, Armstrong SD (2023) Quantifying the fate of nitrogen from cereal rye root and shoot biomass using ^{15}N. Nutr Cycl Agroecosys 125:219–234

Ruis SJ, Blanco-Canqui H, Creech CF, Koehler-Cole K, Elmore RW, Francis CA (2019) Cover crop biomass production in temperate agroecozones. Agron J 111:1535–1551

Sarangi D, Jhala AJ, Govindasamy P, Brusa A (2021) *Amaranthus* spp. Pages 21−41in Chauhan B (ed) Biology and management of problematic crop weed species. San Diego, CA: Academic Press−An imprint of Elsevier.

Sarangi D, Tyre AJ, Patterson EL, Gaines TA, Irmak S, Knezevic SZ, Lindquist JL, Jhala AJ (2017) Pollen-mediated gene flow from glyphosate-resistant common waterhemp (*Amaranthus rudis* Sauer): consequences for the dispersal of resistance genes. Sci Rep 7:44913

Seibert AC, Pearce RB (1993) Growth analysis of weed and crop species with reference to seed weight. Weed Sci 41:52–56

Sellers BA, Smeda RJ, Johnson WG, Kendig JA, Ellersieck MR (2003) Comparative growth of six Amaranthus species in Missouri. Weed Sci 51:329–333

Sias C, Bamber KW, Kumar V, Singh V, Flessner ML (2023) Effects of paraquat application at cover crop planting on cover crop biomass and weed suppression. Weed Technol 37: 494–499

Silva GC, Bagavathiannan M (2023) Mechanisms of weed suppression by cereal rye cover crop: A review. Agron J 115:1571–1585

Singh M, Thapa R, Kukal MS, Irmak S, Mirsky S, Jhala AJ (2022) Effect of water stress on weed germination, growth characteristics, and seed production: a global meta-analysis. Weed Sci 70:621–640

Singh M, Thapa R, Singh N, Mirsky SB, Acharya BS, Jhala AJ (2023) Does narrow row spacing suppress weeds and increase yields in corn and soybean? A meta-analysis. Weed Sci 71: 520–535

Smith RG, Atwood LW, Pollnac FW, Warren ND (2015) Cover-crop species as distinct biotic filters in weed community assembly. Weed Sci 63:282–295

Steckel LE, Sprague CL (2004). Common waterhemp (*Amaranthus rudis*) interference in corn. Weed Sci 52:359–364

Steckel LE, Sprague CL, Stoller EW, Wax LM (2004) Temperature effects on germination of nine Amaranthus species. Weed Sci 52:217–221

Stephens T, Blanco-Canqui H, Knezevic S, Rees J, Kohler-Cole K, Jhala AJ (2024) Integrating fall-planted cereal rye cover crop with herbicides for reducing Palmer amaranth seed production in soybean under planting green conditions. Agrosys Geosci Environ 7:e20507

Sturm DJ, Peteinatos G, Gerhards R (2018) Contribution of allelopathic effects to the overall weed suppression by different cover crops. Weed Res 58:331–337

Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673–680

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385–392

Teasdale JR, Rice CP, Cai G, Mangum RW (2012) Expression of allelopathy in the soil environment: Soil concentration and activity of benzoxazinoid compounds released by rye cover crop residue. Plant Ecol 213:1893–1905

Thapa R, Mirsky SB, Tully KL (2018a) Cover crops reduce nitrate leaching in agroecosystems: a global meta-analysis. J Environ Qual 47:1400–1411

Thapa R, Poffenbarger H, Tully KL, Ackroyd VJ, Kramer M, Mirsky SB (2018b) Biomass production and nitrogen accumulation by hairy vetch–cereal rye mixtures: A meta-analysis. Agron J 110:1197–1208

Thapa R, Tully KL, Reberg-Horton C, Cabrera M, Davis BW, Fleisher D, Gaskin J, Hitchcock R, Poncet A, Schomberg HH, Seehaver SA (2022) Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. Agri Ecosys Envir 326:107823

https://doi.org/10.1017/wsc.2024.99 Published online by Cambridge University Press

Timper P, Davis RF, Webster TM, Brenneman TB, Meyer SLF, Zasada IA, Rice CP (2011) Response of root–knot nematodes and Palmer amaranth to tillage and rye green manure. Agron J 103:813–821

Treadwell DD, Creamer NG, Schultheis JR, Hoyt GD (2007) Cover crop management affects weeds and yield in organically managed sweetpotato systems. Weed Technol 21:1039–1048

USDA-NRCS (2016) Allelopathy and cover crops. Missouri Conservation Practice 340. https://www.nrcs.usda.gov/plantmaterials/mopmstn2825.pdf. Accessed: August 10, 2024

Van den Noortgate W, L´opez-L´opez JA, Marín-Martínez F, Sánchez-Meca J (2013) Three-level meta-analysis of dependent effect sizes. Behav Res Methods 45:576–594

Van Wychen L (2020) 2020 Survey of the most common and troublesome weeds in grass crops, pasture & turf in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. Available: https://wssa.net/wp-content/uploads/2020-Weed-Survey_grass-crops.xlsx

Van Wychen L (2022) 2022 Survey of the most common and troublesome weeds in broadleaf crops, fruits & vegetables in the United States and Canada. Weed Science Society of America National Weed Survey Dataset. Available: https://wssa.net/wp-content/uploads/2022-Weed-Survey-Broadleaf-crops.xlsx

Verret V, Gardarin A, Pelzer E, Médiène S, Makowski D, Valantin-Morison M (2017) Can legume companion plants control weeds without decreasing crop yield? A meta-analysis. Field Crop Res 204:158–168

Wagner-Riddle C, Gillespie TJ, Swanton CJ (1994) Rye cover crop management impact on soil water content, soil temperature, and soybean growth. Can J Plant Sci, 74:485–495

Walters SA, Young BG (2010) Effect of herbicide and cover crop on weed control in no–tillage jack–o–lantern pumpkin (*Cucurbita pepo* L.) production. Crop Prot 29:30–33

Wang G, Ngouajio M, Warncke DD (2008) Nutrient cycling, weed suppression, and onion yield following brassica and sorghum sudangrass cover crops. HortTechnol 18:68–74

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27

Webster TM, Scully BT, Grey TL, Culpepper AS (2013) Winter cover crops influence *Amaranthus palmeri* establishment. Crop Prot 52:130–135

Weisberger D, Nichols V, Liebman M (2019) Does diversifying crop rotations suppress weeds? a meta-analysis. PLoS ONE 14:e0219847

Weisberger DA, Bastos LM, Sykes VR, Basinger NT (2023) Do cover crops suppress weeds in the U.S. Southeast? A meta-analysis. Weed Sci 71(3):244–254

Weisberger DA, Leon RG, Gruner CE, Levi M, Gaur N, Morgan G, Basinger NT (2024) Demographics of Palmer amaranth (*Amaranthus palmeri*) in annual and perennial cover crops. Weed Sci 72:96–107

Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C, Zollinger R (2018) Weed Management in 2050: Perspectives on the future of weed science. Weed Scie 66:275–285

White KE, Brennan EB, Cavigelli MA, Smith RF (2022) Winter cover crops increased nitrogen availability and efficient use during eight years of intensive organic vegetable production. PLoS ONE 17(4): e0267757

Wiggins MS, Hayes RM, Nichols RL, Steckel LE (2017) Cover crop and postemergence herbicide integration for Palmer amaranth control in cotton. Weed Technol 31:348–355

Wiggins MS, Hayes RM, Steckel LE (2016) Evaluating cover crops and herbicides for glyphosate–resistant Palmer amaranth (*Amaranthus palmeri*) control in cotton. Weed Technol 30:415–422

Williams MM, Mortensen DA, Doran JW (1998) Assessment of weed and crop fitness in cover crop residues for integrated weed management. Weed Sci 46:595–603

Wortman SE (2012) Diversification of organic cropping systems with cover crop mixtures: Influence on weed communities, soil microbial community structure, soil moisture and nitrogen, and crop yield. Ph.D dissertation. Lincoln, NE: University of Nebraska–Lincoln. 177 p

https://doi.org/10.1017/wsc.2024.99 Published online by Cambridge University Press

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

Reference	Location	Weed data collection timing[a]	Cover crop type[b]	Cover crop planting method[c]	Termination method[d]	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	PR, PO, PP	PA	CT
Aulakh et al. (2013)	Shorter, AL	E	G, L	D	I	R	H, N	PO	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	PR	PA, RP	CR
Burgos and Talbert (1996b)	Kibler, AR	M	G	D	C	S	H, N	PP	PA	V
Cornelius and Bradley (2017)	Columbia and Moberly, MO	E, L	G, L, B, M	D	C	S	N	-	W	S

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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	PR, PP	SP	C
Currie and Klocke (2005)	Garden city, KS	L	G	D	C	S	H, N	PR	PA	C
Davis (2010)	Urbana, IL	M	G, L	D	I	R, S	H, N	PO	W	S
Dearden (2022)	Ames and Burner, IA	M, L	G	D	C	S	H, N	PR, PO, PP	W	S
DeVore et al. (2012)	Marianna, AR	E, M, L	G	D	C	S	H	PO	PA	CT
DeVore et al. (2013)	Marianna, AR	E, M, L	G	D	C	S	H	PO	PA	S
Hand et al. (2019)	Berrien, Colquitt, Malcon, Worth, and Tift, GA	M, L	G	D	I	R	H	PP	PA	CT
Hand et al. (2021)	Jackson, TN, and Ty Ty, GA	E, M, L	G	D	I	R	H, N	PR, PO, PP	PA	CT
Hay et al. (2019)	Manhattan,	E, M	G	D	C	S	N	-	PA, W	S

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	Hutchinson, and Ottawa, KS									
Koger and Reddy (2005)	Stoneville, MS	M	L	D	C	S	H, N	PP	SP	CR
Koger et al. (2002)	Stoneville, MS	L	G	D	C	S	H, N	PR, PO, PP	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	PP	PA	S
Masiunas et al. (1995)	Champaign, IL Lafayette, IN	E, M	G	D	I, M	R	N	-	RP	V
McMall (2018)	Manhattan, KS	E, M, L	G, L, M	D	C	S	H, N	PR, PO, PP	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	PO, PP	PA	S
Nqouajio and	East	E, M	G, L	BI	I, W	I, S	N	-	RP	V

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Mennan (2005)	Lansing, MI									
Nunes et al. (2023)	Brooklyn, WI Carbondale, IL Rock Springs, PA Rossville, KS	M	G	D	C	S	H, N	PR	M	S
Oys (2022)	Mead and Clay Center, NE	E, L	G, L	D	C	S	H, N	PO	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	*	PA, RP	CT
Price et al. (2016)	Barbour, AL Macon, Seminole, and Worth, GA	L	G	D	C	S	H	PP	PA	CT

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	Calhoun and Lee, SC Tipton, TN									
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	PP	PA	CT
Treadwell (2007)	Goldsboro, NC	L	M	D	M	I, R	N	-	M	V
Walter and Young (2010)	Carbondale, IL	L	G	BC	I	R	H, M, N	*	RP	V
Wang (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	*	PA	CT
Wiggins et al. (2017)	Jackson, TN	E	G, L	D	C	S	N	-	PA	S
Williams et al.	Ithaca, NE	E, M	G, L	D	C	S	N	-	M	S

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(1998)										
Wortman (2012)	Mead, NE	E	M	BI	M	I, R	M	-	RP	CR, S

[a]E, early-season (0–4 weeks after crop planting); M, mid-season (5–8 weeks after crop planting); L, late-season (>8 weeks 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, winter-kill.

[e]I, incorporated; R, rolled; S, standing.

[f]H, herbicide; M, mechanical; N, no weed control method used.

[g]PR, pre-emergence; PO, post-emergence; PP, pre followed by post-emergence.

[h]M, Mixed (mixed population of *Amaranthus* species); PA, Palmer amaranth; RP, redroot pigweed; SP, smooth pigweed; W, waterhemp.

[i]CR, corn; CT, cotton; S, soybean; V, vegetable.

[*]Data were averaged across herbicide application timings and in-season weed management method.

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Table 2: Estimated coefficients from the linear meta-regression model between cover crop biomass, and time between cover crop termination and subsequent crop planting as predicator variable, and *Amaranthus* spp. weed density and *Amaranthus* spp. weed biomass as response variable

Predictor	Response	Intercept	Slope	N	r^2	p-value
Cover crop biomass	density	-0.0053	-0.00017	360	0.298	<0.0001
	biomass	-0.2884	-0.00007562	110	0.486	0.0568
Time between cover crop 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

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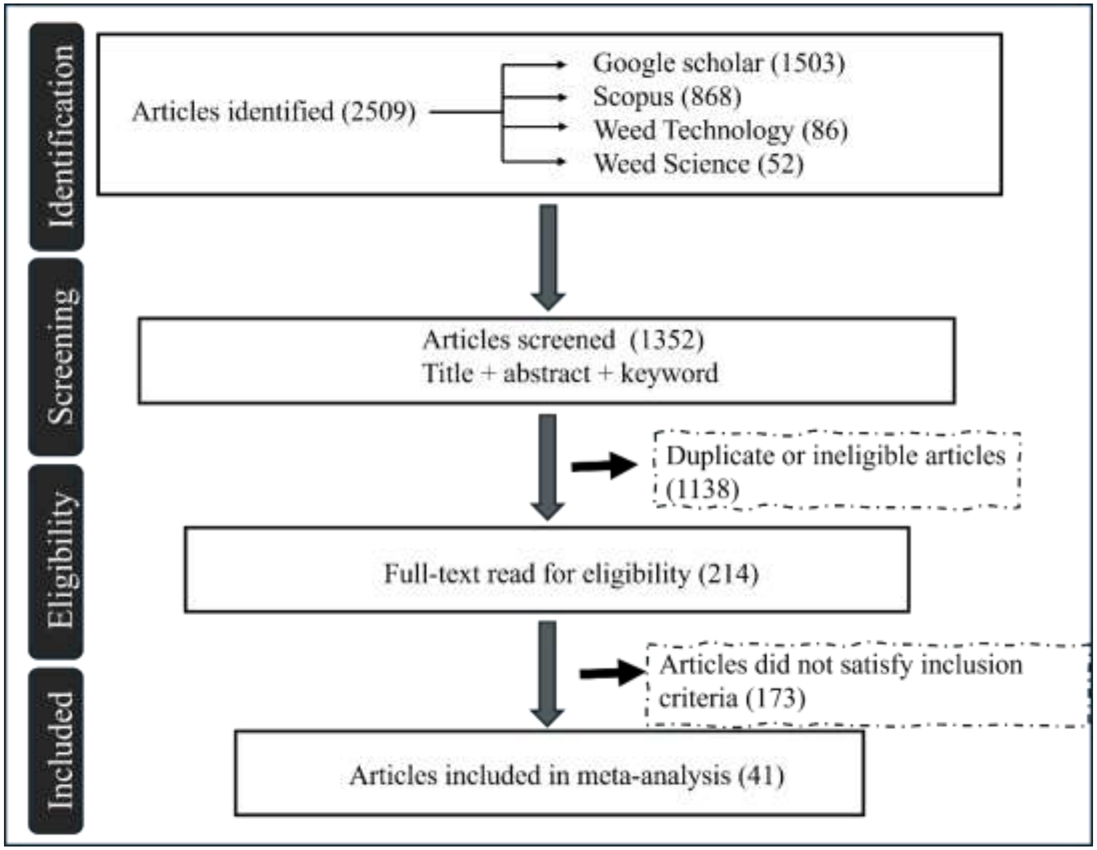

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Page et al. 2021) flow diagram explaining the systematic procedure used for selecting articles included in the meta-analysis.

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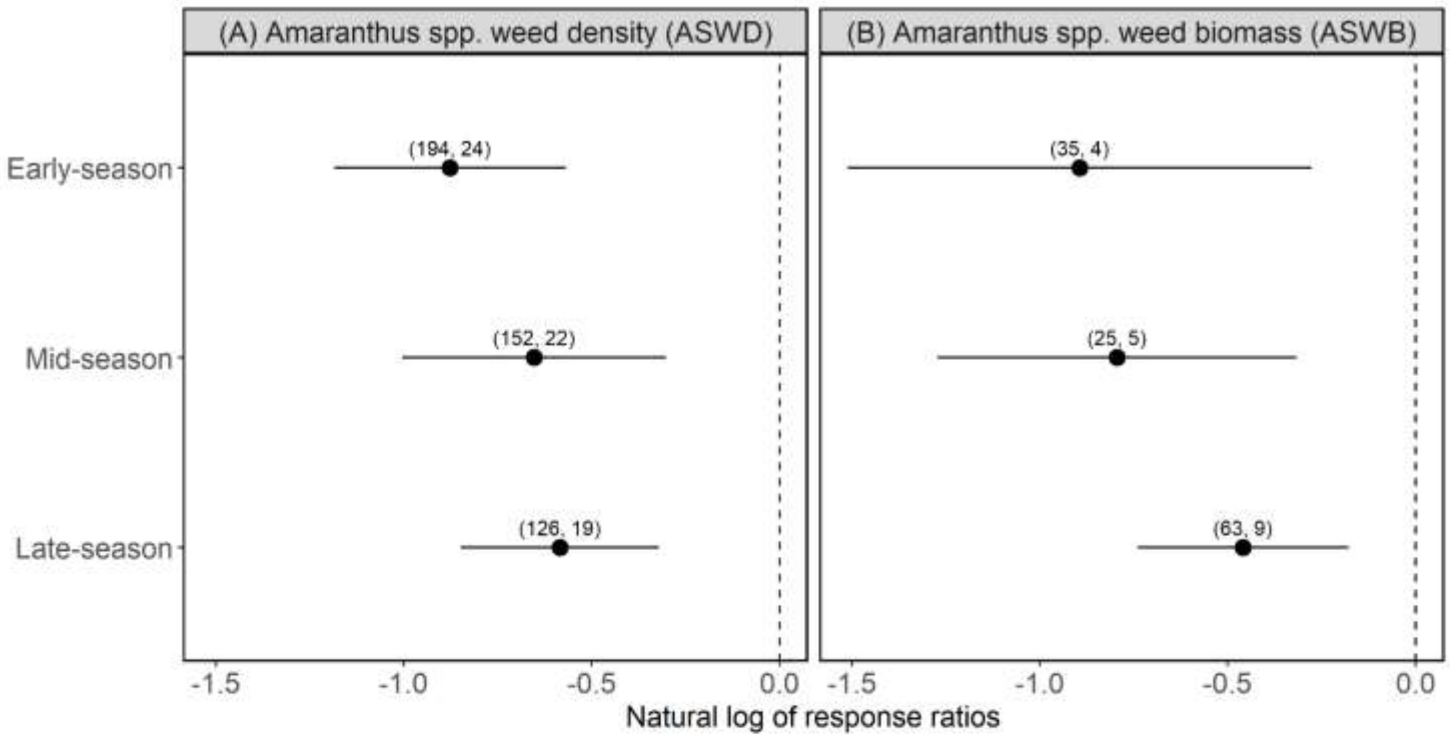

Figure 2. Overall effect of cover crops on (A) *Amaranthus* spp. weed density, and (B) *Amaranthus* spp. weed biomass at different weed data collection timings (early, mid, and late-season). Early, mid, and late-seasons were 0–4, 5–8, and >8 weeks after crop planting, respectively. The numbers in the parenthesis represent the number of paired observations followed by the number of articles reporting each effect size. The vertical black dotted 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.

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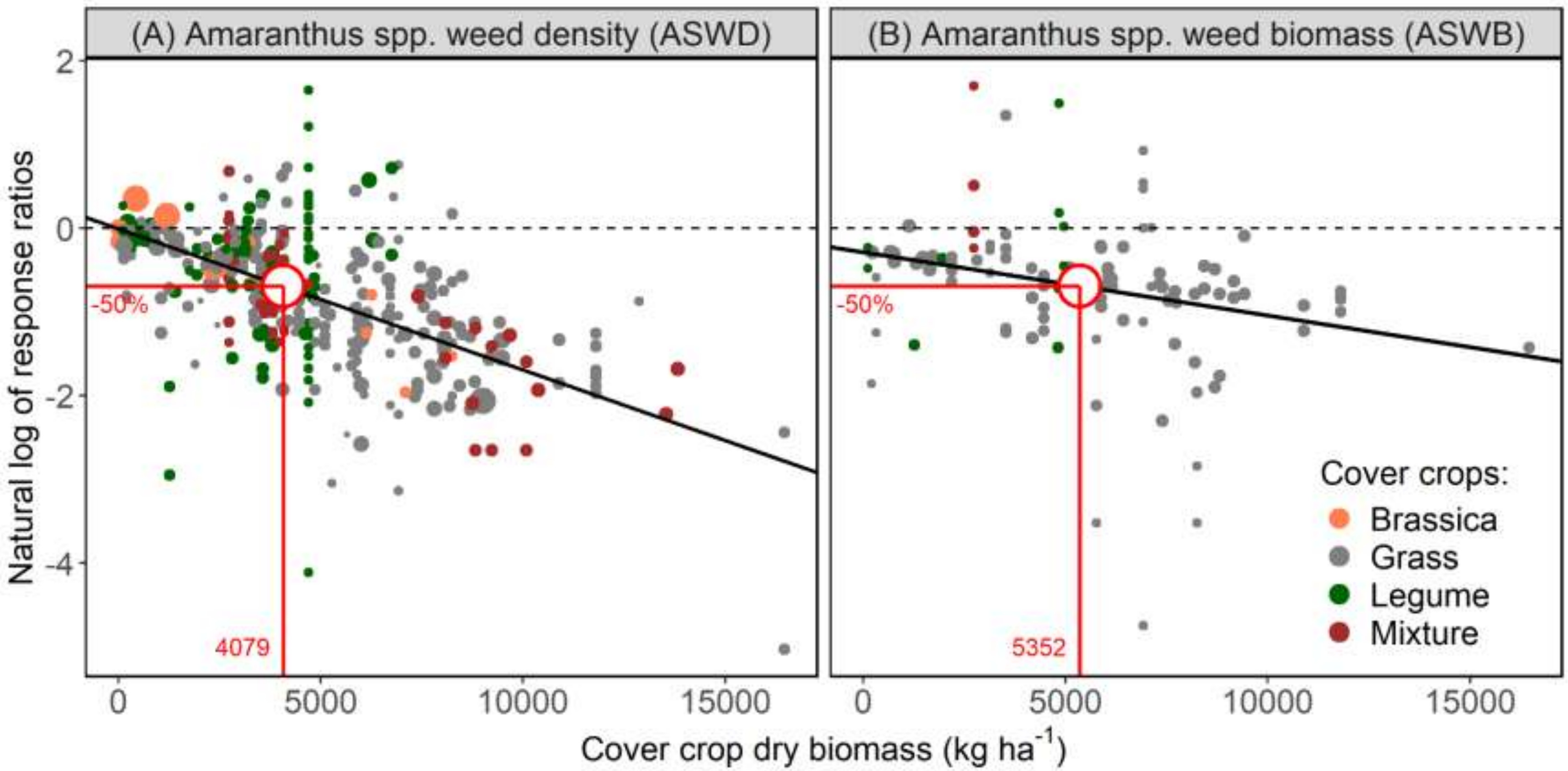

Figure 3. Bubble plots representing (A) *Amaranthus* spp. weed density (ASWD), and (B) *Amaranthus* spp. weed biomass (ASWB) natural log response ratio as a function of cover crop (CC) biomass (kg ha^{-1}). The color of the bubble represents the CC species, whereas the size of the bubble is based on the sample size (i.e., weights assigned for individual natural log response ratio). The vertical black dotted line, and solid black line represent zero effect, and fitted regression model. 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.

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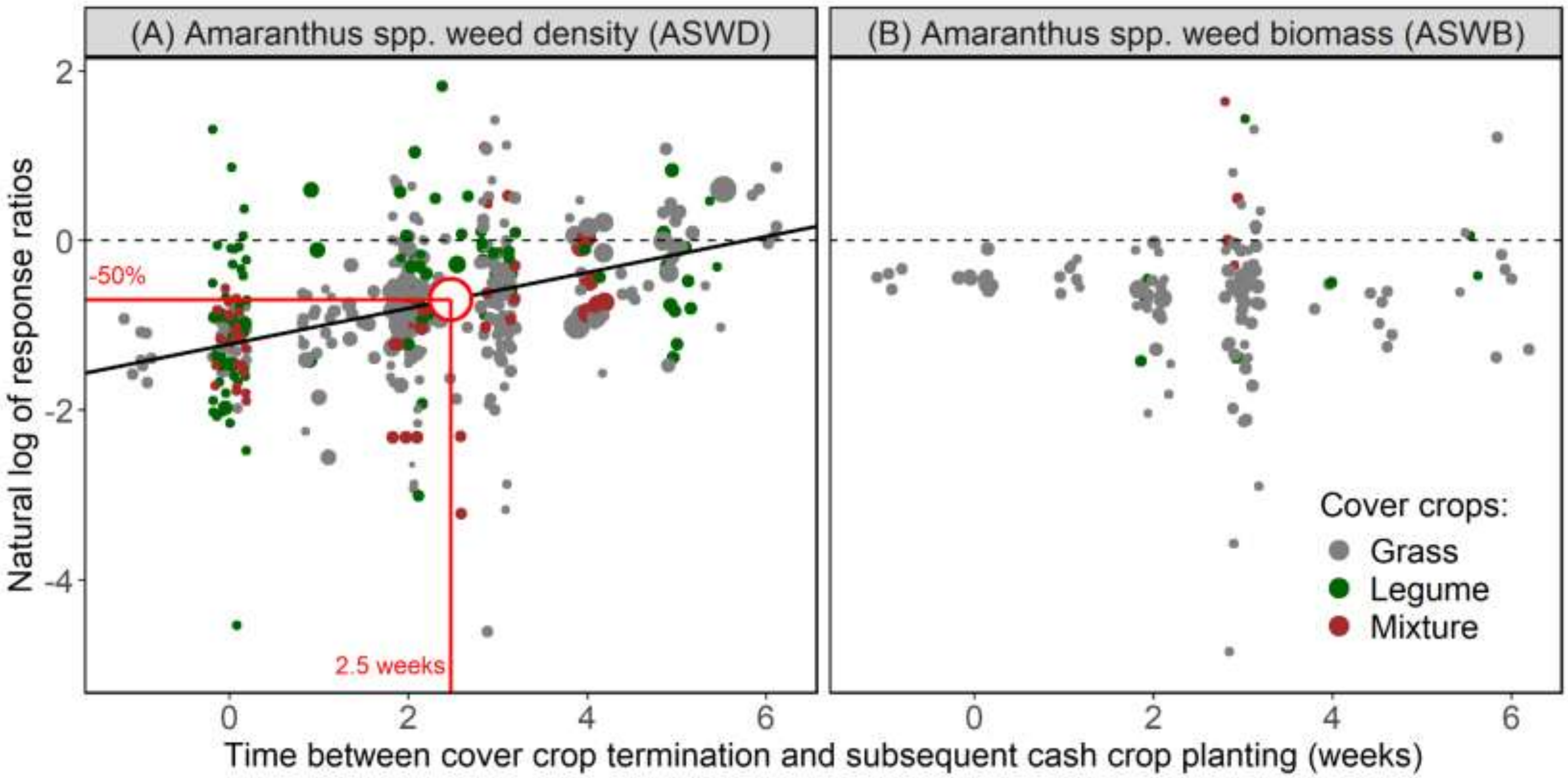

Figure 4. Bubble plots representing (A) *Amaranthus* spp. weed density (ASWD), and (B) *Amaranthus* spp. weed biomass (ASWB) natural log response ratio as a function time interval (weeks) between cover crop (CC) termination and subsequent crop planting. The color of the bubble represents the CC species,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

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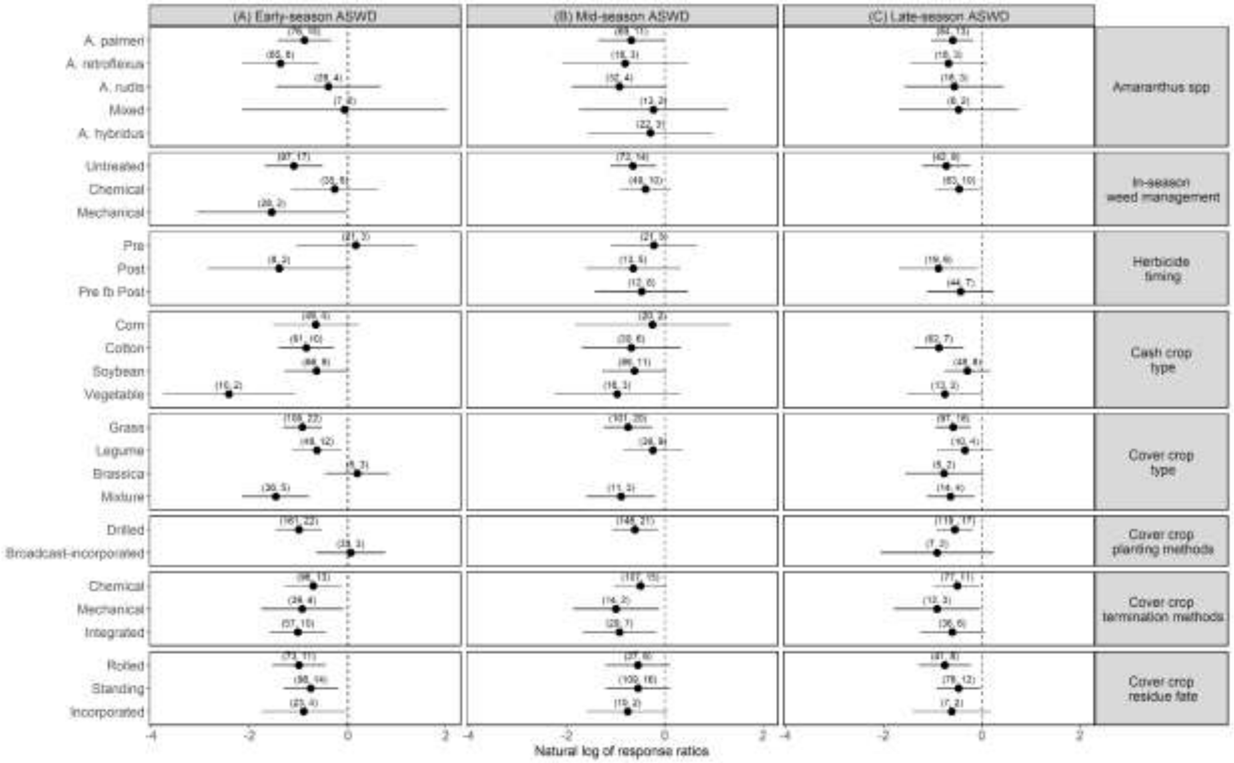

Figure 5. The effect of cover crops (CCs) on *Amaranthus* spp. weed density at (A) early-season [0–4 weeks after row crop planting (WAP)], (B) mid-season (5–8 WAP), and (C) late-season (>8 WAP) as impacted by individual *Amaranthus spp*., cash crop type, crop in-season weed management strategy, herbicide application timing, CC functional group, planting method, termination method, and residue fate. The numbers in the parenthesis represent the number of paired observations followed by number of articles reporting each effect size. The vertical black dotted 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 size were deemed significantly different at 1% level of significance.

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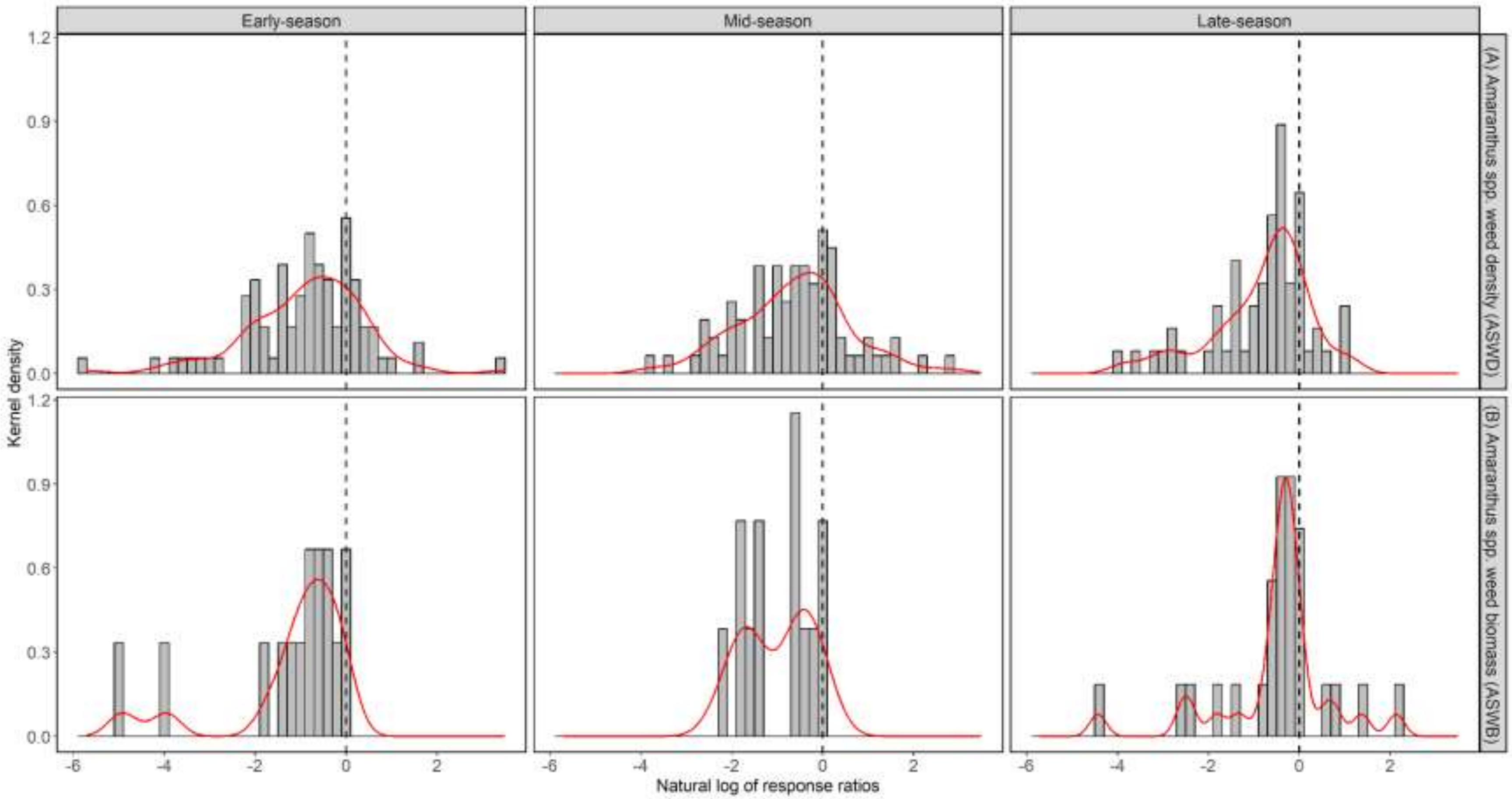

Figure 6. Density plot showing the distribution of individual effect sizes (natural log of response ratios) of (A) *Amaranthus* spp. weed density (ASWD), and (B) *Amaranthus* spp. weed biomass (ASWB) at early [0–4 weeks after crop planting (WAP)], mid (5–8 WAP) and late-season (>8 WAP) weed data collection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

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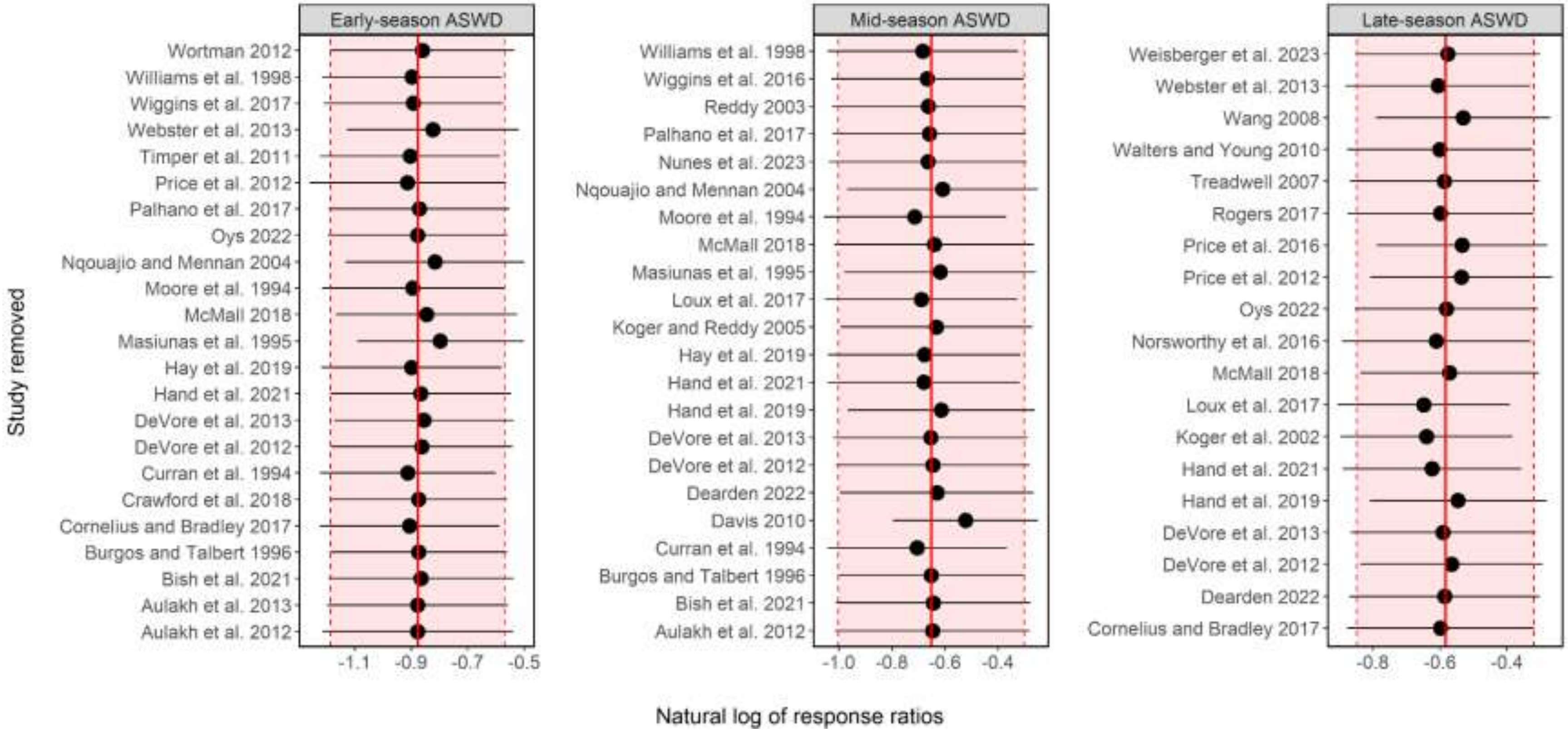

Figure 7. Sensitivity analysis conducted using *jackknife* procedure representing no impact of any single study removal on the overall effect sizes (log of response ratios [ln(RR)]) of cover crop effects on early, mid, and late-season *Amaranthus* spp. weed density (ASWD). The vertical red solid, and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

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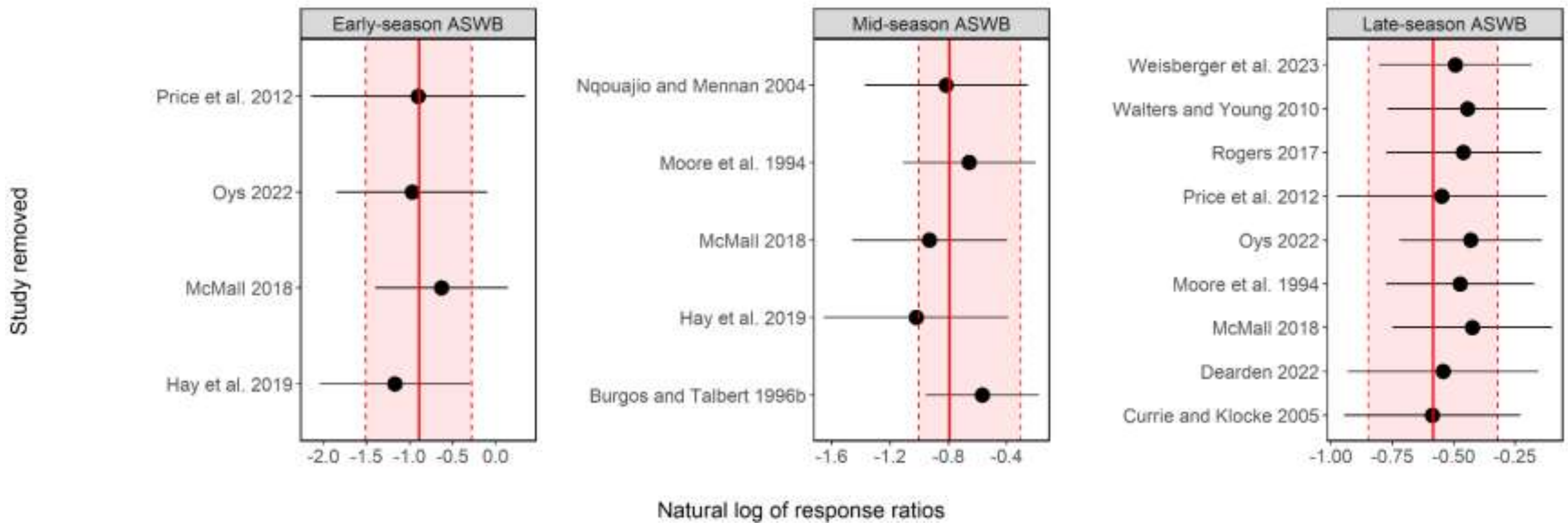

Figure 8. Sensitivity analysis conducted using *jackknife* procedure representing no impact of any single study removal on the overall effect sizes (log of response ratios [ln(RR)]) of cover crop effects on early, mid, and late-season *Amaranthus* spp. weed biomass (ASWB). The vertical red solid, and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

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