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# Meta-analytic insights on cover crop weed suppression in the midsouthern United States

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## Abstract

Herbicide resistance poses an escalating challenge to successful weed management in contemporary cropping systems, prompting growing interest in integrated strategies to reduce reliance on herbicides. Although cover cropping has long been recognized for its potential to suppress weeds, it has recently gained renewed attention as a weed management tool and for its ability to help producers achieve broader goals of soil health and environmental sustainability. Although research on its efficacy in the midsouthern United States has accumulated, a meta-analytic synthesis has been lacking. This meta-analysis synthesized 746 effect sizes from 27 peer-reviewed studies (selected based on explicit reporting of weed suppression metrics, conducted in the midsouthern United States between 1991 and 2023) to assess cover crop weed suppression in the midsouthern region, which includes Alabama, Arkansas, Louisiana, Mississippi, eastern Oklahoma, Tennessee, and eastern Texas. Six key moderators and their two-way interactions were evaluated: tillage status of no-cover-crop controls, cover crop termination timing, weed control evaluation timing, cover crop type, weed functional group, and crop type, using a multivariate framework capturing study-level variation. The overall effect size was 36 (confidence interval [CI], 25–47], with most moderator levels showing positive effect sizes. Suppression was pronounced against no-till controls (mean difference [MD] = 43; CI, 30–55), while tilled controls exhibited moderated effects (MD = 27; CI, 14–39) due to the inherent weed suppression provided by tillage. Effects were greater for early evaluation timing (MD = 47; CI, 33–61) than late timing (MD = 34; CI, 20–48). Grass-legume mixtures provided the greatest suppression (MD = 70; CI, 56–84), while brassicas were ineffective (MD = 13; CI, 0–27). However, substantial two-way interactions among these moderators were prevalent, accompanied by high heterogeneity, indicating complex context specificity. Nonetheless, these findings highlight the weed suppression potential of cover crops and provide agroecologically informed quantitative insights into using cover crops for weed management in the region.

## Introduction

The progressive decline in the efficacy of conventional weed control methodologies, driven by the proliferation of herbicide resistance and heightened environmental concerns, poses a formidable threat to the sustainability of crop production systems (Heap 2014; MacLaren et al. 2020; Norsworthy et al. 2012). This issue is particularly pronounced in the midsouthern United States, a region characterized by protracted warm growing seasons, persistent weed seedbanks, and the dominance of aggressive taxa such as Palmer amaranth (*Amaranthus palmeri* S. Wat.) and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], which collectively pose significant agronomic challenges (Webster and Nichols 2012). The region's intensive row-crop agriculture, which is dominated by cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and rice (*Oryza sativa* L.), creates ideal conditions for weeds to thrive and adapt, while imperfect crop rotations, the extensive use of no-tillage systems, and widespread adoption of new herbicide technologies further exacerbate resistance issues (Green and Owen 2011). Glyphosate-resistant weeds such as Palmer amaranth, horseweed (*Conyza canadensis* L.), and ryegrass (*Lolium perenne* L. spp. *multiflorum* Lam.) are prevalent, with many exhibiting resistance to multiple herbicide sites of action (Heap 2025; Heap and Duke 2018).

Cover crops (CCs) are increasingly recognized as a key component of sustainable agriculture, offering benefits such as weed suppression, soil and environmental health enhancement, and reduced dependence on chemical inputs (Drinkwater et al. 1998; Mirsky et al. 2013; Teasdale 1996; Webster et al. 2013). Economic analyses also support long-term CC adoption, suggesting benefits like reduced herbicide inputs, improved soil organic matter, and enhanced crop yields that may offset establishment costs (Bergtold et al. 2017; Fernando and Shrestha 2023; Peng et al. 2024; Schnitkey et al. 2024; Synder et al. 2016). Weed suppression by CCs is achieved through multiple mechanisms, including physical competition for light, water, and nutrients, as well as allelopathic effects that inhibit weed germination and growth (Weston 1996). Studies have demonstrated that CCs can significantly reduce weed biomass by up to 90% compared to fallow systems (Brennan and Smith 2005; Mirsky et al. 2013). In addition to weed control, CCs enhance soil structure, increase organic matter, and reduce erosion, thereby contributing to long-term agricultural productivity (Blanco-Canqui et al. 2015). As herbicide resistance and environmental concerns grow, CCs offer a viable, ecologically sound strategy for integrated weed management (Ryan et al. 2011).

Previous meta-analyses have predominantly neglected the midsouthern United States, thereby constraining comprehensive insights into its agroecological dynamics (Nichols et al. 2020; Weisberger et al. 2023). This study addresses this gap by leveraging an extensive data set to investigate how CC management and other relevant contexts influence weed suppression across the mid-southern region. In the midsouth, erratic frost patterns and heavy clay soils critically limit CC termination timing, primarily through their impact on biomass accumulation and field access. Typically, frost occurs between mid-November and mid-December, which can curtail growth potential for fall-planted CCs (Balkcom et al. 2023; Haramoto and Pearce 2019; Keene et al. 2017). This contrasts with weather in the Midwest, where cooler and more stable temperatures support reliable biomass growth, leading to more predictability in crop management practices (Qin et al. 2023). Additionally, clay-rich soils retain moisture longer after rainfall, further delaying timely operations. The implications of these regional constraints underline the necessity for adaptive termination strategies that optimize biomass production and enhance weed suppression. Similarly, while the mild winters in the Southeast facilitate greater CC biomass production (Reberg-Horton et al. 2012), high precipitation accelerates residue decomposition, reducing the duration of weed suppression (Weisberger et al. 2023). These regional distinctions demand midsouth-specific management strategies.

Contradictory findings exist across multiple CC management variables. For instance, grass-legume mixtures such as cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) have demonstrated weed suppression in certain regions (Brennan and Smith 2005); however, their efficacy can vary in the midsouth due to accelerated residue decomposition and the prevalence of heat-tolerant weed species (Mirsky et al. 2013). While temperate studies have highlighted the consistency of grass-legume mixtures, the temporal limitation may obscure the nuanced long-term impacts of crop residues. The adaptability of these mixtures to subtropical systems requires further investigation. Likewise, brassica CCs (e.g., rapeseed [*Brassica napus* L.] and legumes [e.g., hairy vetch]), valued for nitrogen fixation and soil structure improvement abilities, are often observed to fail to maintain suppression under southern conditions characterized by rapid mineralization and weed adaptation (Mirsky et al. 2011). The functional diversity of weed communities may further modulate CC performance. Broadleaf species such as *Amaranthus* spp. are particularly responsive to light attenuation by residue layers, whereas graminoids (e.g., *Echinochloa* spp.) and sedges (e.g., *Cyperus* spp.) exploit moisture-retaining, residue-rich, no-till environments (Smith et al. 2011; Teasdale 1996). These context-dependent outcomes also highlight the need for a meta-analytic synthesis to optimize CC strategies for weed suppression.

This research offers meta-analytic insights into CC-mediated weed suppression by examining six critical moderators and their interactions: tillage status of no-CC controls (TS-NCC), CC termination timing (CC-Term time), weed control evaluation timing (WC-Eval time), CC type (CC type), weed functional group (Weed FG), and crop type. By advancing the understanding of these dynamics in the regional context, the study emphasizes the need for context-specific strategies. The findings address existing knowledge gaps and provide a general CC employment framework for stakeholders to optimize weed management outcomes in the region, especially amid escalating herbicide resistance.

## Materials and Methods

### Data Collection

A comprehensive literature search was conducted in early 2024 using Web of Science (https://webofscience.com), Scopus (https://scopus.com), and Google Scholar (https://scholar.google.com) that identified 27 studies conducted between 1991 and 2023 focused on CC-mediated weed suppression in midsouthern U.S. cropping systems. Only studies that explicitly reported weed suppression under no-herbicide conditions were considered to ensure an unbiased assessment of CC effects. The Boolean search string used was: (“cover crop” OR “cover crops”) AND (“weed”) AND (“cereal rye” OR “grass” OR “legume” OR “brassica”). Additional studies were identified through backward citation tracking. To maintain study relevance, inclusion criteria required that articles report measures of weed suppression (percent weed control, weed biomass, or weed density) and include a no-CC control treatment. Studies were filtered to include only those conducted in the midsouthern United States covering Alabama, Arkansas, Louisiana, Mississippi, eastern Oklahoma, Tennessee, and eastern Texas. Only peer-reviewed journal articles and recent master’s or Ph.D. theses were considered.

A total of 27 publications (listed in Figure 1) met all criteria, yielding 746 paired comparisons of weed suppression variables with corresponding error measures and replication details. Error metrics such as confidence interval (CI), coefficient of variation, mean squared error (MSE), and standard error (SE) were converted to standard deviations using established statistical methodologies (Hedges et al. 1999). MSE estimates from balanced studies using post hoc letter results were calculated using MSEFindR (Garnica et al. 2024). Data extraction from graphical sources was performed using calibrated scale conversion in Adobe Illustrator (Adobe Inc., San Jose, CA).

Moderator variables were standardized prior to analysis. The TS-NCC was categorized into no-till and tilled, based on reported soil management practices. CC-Term time was grouped into five intervals: 0–1 wk before planting (WBP), 2–3 WBP, 4–5 WBP, ≥6 WBP, and no termination. The WC-Eval time was harmonized into four categories: at or before planting, early season (1–3 wk after planting), mid-season (4–6 wk after planting), and late season (≥6 wk). The CC type was classified into functional groups: grasses (e.g., cereal rye, wheat [*Triticum aestivum* L.], barley [*Avena fatua* L.], oat [*Avena sativa* L.], legumes [e.g., hairy vetch and Austrian winter pea], brassicas [e.g., radish, *Raphanus sativus* L. and yellow mustard, *Sinapis alba* L.], and grass-legume mixtures [e.g., cereal rye + hairy vetch]). The Weed FG data were recorded as broadleaf, grass, sedge, or all weeds, depending on the dominant target species reported. The crop type was standardized into four groups: corn, cotton, soybean, and other crops.

### Effect Size Calculation

The mean difference (MD) was used as the effect size metric, calculated as: $MD = \overline{X}_{treatment} - \overline{X}_{control,}$ where $\overline{X}_{treatment}$ represents the mean value of weed suppression under CC treatments and $\overline{X}_{control}$ represents the mean value for the no-CC control. The MD was chosen because it provides an absolute measure of treatment efficacy, which is crucial given that all weed suppression variables were converted to a standardized percentage scale (−100% to 100%). While the log response ratio (LRR) is an alternative metric that accounts for high variance across studies (Philibert et al. 2012), previous meta-analyses have found that it excludes a significant proportion of data when treatment or control values approach zero (Weisberger et al. 2023). Given that percent weed control data contain a substantial number of zero values, MD was deemed the most appropriate metric.

### *Data Analysis*

All data processing, statistical analyses, and visualizations were conducted in R (v.4.4.1) (R Core Team 2025). A multivariate meta-analysis was implemented using the *rma.mv* function in the METAFOR package (Viechtbauer 2010) to assess the effects of CCs on weed suppression across varying management conditions, with MD as the effect size metric. The hierarchical structure of the data —where multiple effect sizes were nested within publications— was accounted by specifying random effects for publication nested with the six moderators. An initial overall meta-analysis estimated the general effect of CCs on weed suppression. This was followed by single-moderator models to individually evaluate the six key factors, parameterized without an intercept to treat each level independently. Two-way interaction models were then constructed to test whether the effect of one moderator was contingent on another moderator. For interaction models, data were filtered to exclude levels with sparse observations to ensure model stability. All models were fitted using restricted maximum likelihood (REML) estimation with the *optim* optimizer and degrees of freedom adjusted via the containment method (dfs = "contain") to account for random effects. Model fit was assessed using likelihood ratio tests (LRTs) comparing nested models fitted with maximum likelihood (ML), while final parameter estimates used REML for unbiased variance components. Fixed effects (six moderators independently and their two-way interactions: TS-NCC, CC-Term time, WC-Eval time, CC type, Weed FG, and crop type) were tested with Wald-type *F*-tests, adjusted for the hierarchical structure. Pairwise comparisons among moderator levels were performed using the *btt* argument to test the null hypothesis that individual coefficients were equal ($H_0$: $\beta_i = \beta_j = \ldots$), without assigning reference levels. To adjust for multiple comparisons using *Bonferroni* method and assign compact letter displays for significant within-group differences, post hoc tests ($P < 0.05$) were conducted using the *glht* function from the MULTCOMP package (Hothorn et al. 2008).

### *Assessment of Heterogeneity and Publication Bias*

Residual heterogeneity was quantified using variance components ($\sigma^2$) to determine the proportion of variability attributable to study-level factors. Unexplained heterogeneity was quantified using $I^2$ statistics derived from multilevel variance components to estimate the proportion of total variability attributable to study-level differences (Higgins et al. 2003). Publication bias was assessed via a jackknife sensitivity analysis, assessing the robustness of the overall weed suppression effect size by iteratively excluding each of the 27 publications ($k = 746$ effect sizes) and refitting the multivariate random-effects model with publication as the random effect.

## Results and Discussion

While individual MDs are bounded between −100% and 100% by definition, model-based CIs are not constrained to this range. Meta-analytic estimates incorporate variance across studies, and in cases with sparse data or high heterogeneity, CI bounds may exceed these limits. These intervals should be interpreted in the context of model uncertainty, not as observed values. In figures, confidence intervals were trimmed at −100 to 100% to reflect the bounds of MD calculations and aid visual interpretability. This does not affect model estimation or inference.

The jackknife sensitivity analysis showed individual estimates ranging narrowly from 34 to 38 (mean MD = 36), with a jackknife-derived SE of 5.27, indicating minimal influence of any single study on the pooled effect (Figure 1A). This stability reinforces the reliability of CC-mediated weed suppression despite high between-publication heterogeneity, which likely reflects systematic contextual variation rather than study-specific outliers (Pittelkow et al. 2015). Building on this robust foundation, the baseline model showed an overall weed suppression effect of 36 ± 5.3 ($t_{26} = 6.78$; $P < 0.001$; CI, 25–47), with individual paired effect sizes spanning −100 to 100 (Figure 1B), substantiating CCs as a viable weed management strategy in midsouthern U.S. agroecosystems. However, the wide CI and elevated heterogeneity ($I^2 \approx 89.5\%$), entirely attributable to publication-level differences, highlight substantial variation necessitating further exploration of moderating factors. Despite high $I^2$ and wide CI, the stability observed in the sensitivity analyses confirms the robustness of the pooled estimate to individual studies, affirming the integrity of CC-mediated weed suppression as a consistent baseline for mid-southern systems, supporting subsequent moderator analyses amid diverse experimental conditions.

The influence of data type (weed density, weed control, weed biomass) used to quantify CC-mediated weed suppression was statistically significant ($F_{3,39} = 9.02$, $P = 0.0001$), yielding effect sizes of 43 (SE = 8.4; CI, 26–59; $k = 451$) for weed density, 32 (SE = 8.3; CI, 15–48; $k = 281$) for weed control, and 37 (SE = 20.2; CI, 4–78; $k = 14$) for weed biomass (Figure 1C). The limited precision for weed biomass estimates reflects fewer contributing studies. Although the overlapping CIs and comparable effect magnitudes (MD = 32–43) among the variables indicate no practically meaningful differentiation, they are statistically distinct and contrast with prior meta-analyses in which weed biomass and density (e.g., Nichols et al. 2020; Osipitan et al. 2018; Weisberger et al. 2023) were selectively significant using log response ratios (LLRs), without incorporating percent weed control data. Here, converting density and biomass into percent weed control equivalents enabled the MD approach. The consistency across metrics, absent in LLR-based syntheses, despite high heterogeneity ($I^2 = 89.5\%$) justified pooling these data types for subsequent moderator analyses. The observed heterogeneity likely reflects systematic differences in study design, environmental conditions, CC species, and weed community composition—factors that can be variable across midsouth weed management contexts.

### *Tillage Status of No-Cover Crop Controls*

A multivariate meta-analysis established statistically significant effects of TS-NCC on weed suppression effect size ($F_{2,744} = 51.16$; $P < 0.001$). Effect sizes against no-till control plots were pronounced (MD = 43; CI, 30–55; $k = 535$), exceeding those against tilled control plots (MD = 26; CI, 14–39; $k = 211$) (Figure 2A). Substantial residual heterogeneity ($I^2 = 94.1\%$; $P < 0.001$) was present,

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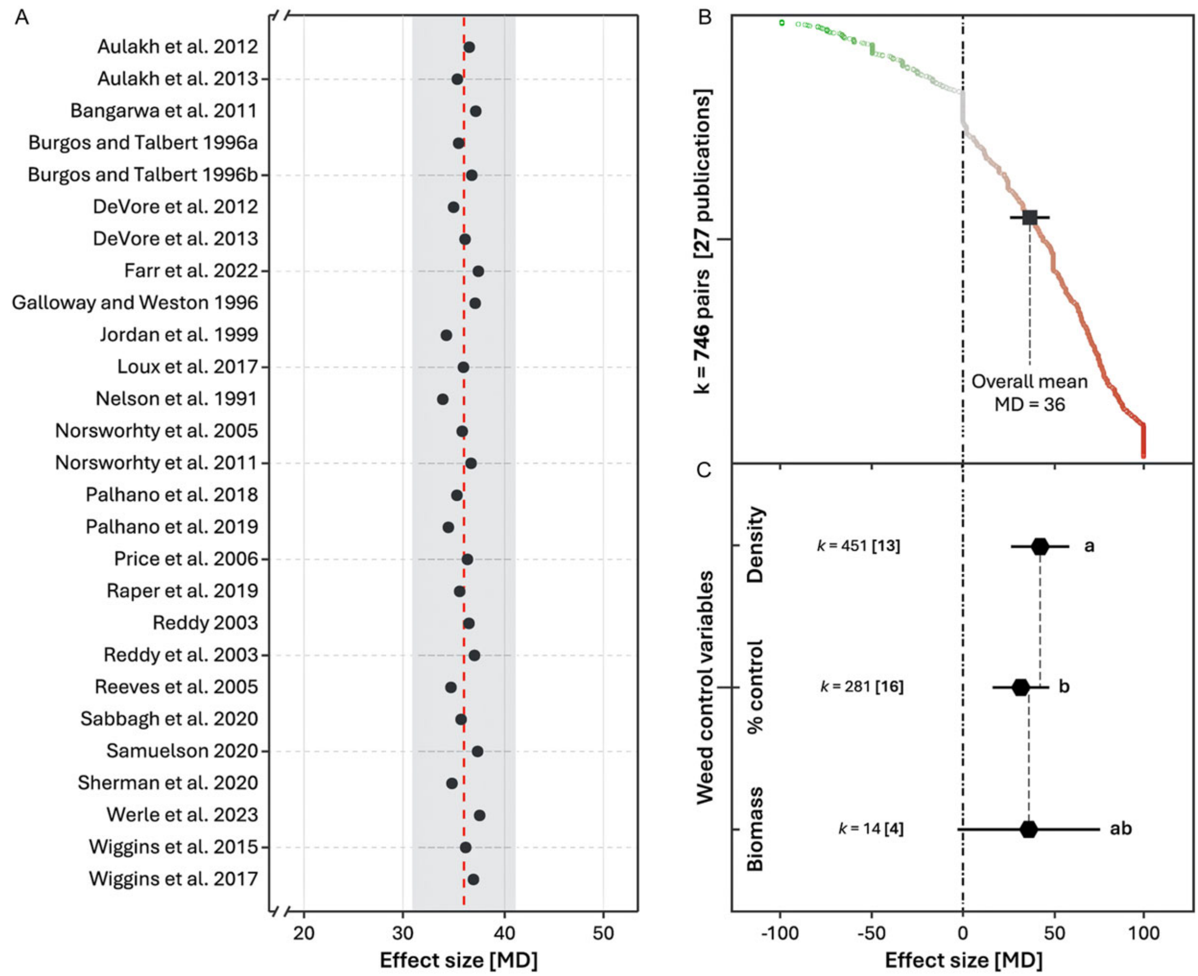


**Figure 1.** (A) Jackknife sensitivity analysis of the overall effect size (MD) across 27 publications. Each point represents the MD estimate after iteratively excluding one publication, with the vertical line indicating the overall MD (36.00) and the standard error (±5.31, gray band). (B) Distribution of 746 paired effect sizes from 27 publications for weed suppression, with overall mean and CI. (C) Effect sizes (MD) for weed suppression across different data types (weed density, weed control, and weed biomass). Solid horizontal bars represent CI, and dotted vertical lines are the main effects of the primary moderator. Letters denote significant within-group differences ($P < 0.05$). Abbreviations: CI, confidence interval; *k*, number of effect sizes included for each group; MD, mean difference. Numbers in brackets represent the number of publications from which the data originated.

indicating the context-dependent nature of weed suppression, with variance components showing pronounced contributions from Weed FG $I^2 = 31.4\%$; CC type $I^2 = 22.9\%$; CC-Term timing $I^2 = 19.5\%$; and WC-Eval timing $I^2 = 18.4\%$.

Interactions between TS-NCC and CC-Term timing ($\chi^2(4) = 36.93$; $P < 0.001$) and WC-Eval timing ($\chi^2(2) = 155.64$; $P < 0.001$) significantly modulated effect sizes, yet residual heterogeneity persisted ($I^2 = 93.1\%$; $P < 0.001$), indicating limited explanatory power. Against tilled controls, CC-Term timing effects were consistently significant (e.g., 2–3 WBP: MD = 22; CI, 11–33; $k = 77$; 4–5 WBP: MD = 27; CI, 17–38; $k = 32$), except for nonterminated CCs (MD = 48; CI, −17 to 112; $k = 20$) (Figure 2B). Against no-till controls, effects varied markedly (e.g., nonterminated: MD = 67; CI, 2–131; $k = 18$; 0–1 WBP: MD = 13; CI, −1 to 27; $k = 12$). WC-Eval timing against tilled controls peaked at early season (MD = 55; CI, 42–68; $k = 48$) relative to mid-season (MD = 13; CI, 1–26; $k = 119$) and late-season (MD = 37; CI, 24–49; $k = 44$), while no-till controls exhibited more uniform effects (e.g., early: MD = 43; CI, 30–55; $k = 149$; mid: MD = 36; CI, 24–49; $k = 71$) (Figure 2C).

Interactions with CC type ($\chi^2(3) = 15.60$, $P = 0.001$), Weed FG ($\chi^2(3) = 90.51$, $P < 0.001$), and crop type ($\chi^2(2) = 72.96$, $P < 0.001$) further delineated effects, with residual heterogeneity ranging from $I^2 = 93.1\%$ to 94.7%. Grass-legume mixtures against tilled controls were most effective (MD = 62; CI, 50–75; $k = 12$), while brassica CCs were nonsignificant (MD = 19; CI, −23 to 62; $k = 46$) (Figure 2D). Against no-till controls, brassica CCs were marginally significant (MD = 15; CI, 3–28; $k = 93$) compared to the grass-legume mixture (MD = 51; CI, 34–68; $k = 8$). There were only minor differences in effect sizes among Weed FG against tilled controls, however, against no-till controls, sedges did not exhibit a significant effect (MD = −13; CI, −36 to 10; $k = 2$) (Figure 2E). Cotton against tilled controls showed reduced suppression (MD = −26; CI, −50 to −2; $k = 54$) (Figure 2F).

The TS-NCC fundamentally governs the observed magnitude of CC-mediated weed suppression. No-till controls amplify effect sizes due to elevated baseline weed pressure in the absence of soil disturbance, whereas tilled controls attenuate apparent efficacy through mechanical weed abatement (Nichols et al. 2015). This contrast underscores the need to standardize TS-NCC in meta-analyses to avoid biased interpretations of CC performance. Persistent heterogeneity and variance in Weed FG and CC type arise from differential suppression efficacy, as CC types such as grass-legume mixtures strongly suppress broadleaves and sedges

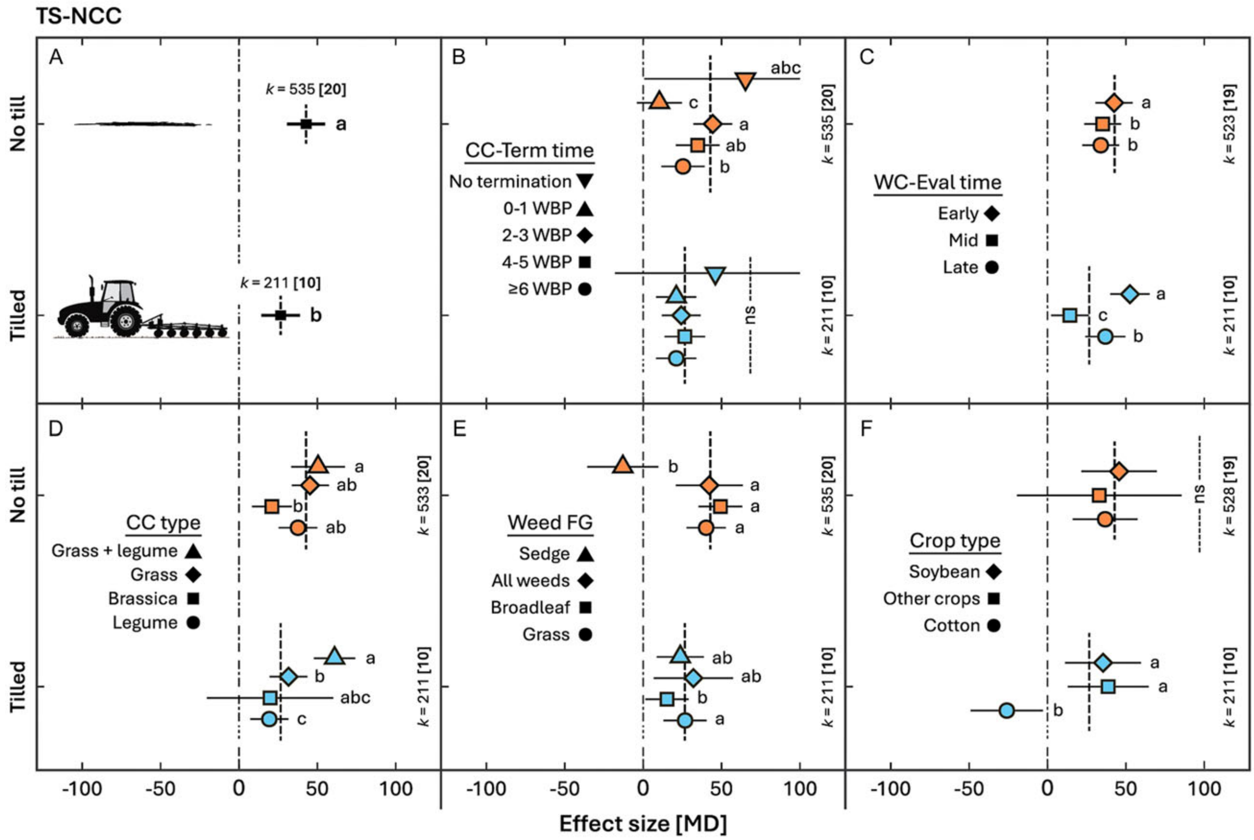


**Figure 2.** Effect sizes (MD) for TS-NCC and its interactions with other moderators. (A) Main effects of TS-NCC. (B) Interaction between TS-NCC and CC-Term time. (C) Interaction between TS-NCC and WC-Eval time. (D) Interaction between TS-NCC and CC type. (E) Interaction between TS-NCC and Weed FG. (F) Interaction between TS-NCC and crop type. Solid horizontal bars represent CI, dotted vertical lines represent the main effects of the primary moderator. Letters denote significant within-group differences ($P < 0.05$). CIs were truncated at ±100% for interpretability. Abbreviations: CC-Term time, cover crop termination timing; CC type, cover crop type; CI, 95% confidence interval; *k*, number of effect sizes included for each group; MD, mean difference; TS-NCC; tillage status of no-cover-crop controls; WC-Eval time, weed control evaluation timing; Weed FG, weed functional group. Numbers in brackets represent the number of publications from which the data originated.

with high biomass and allelopathy, while brassicas and legumes exert weaker, less consistent effects across weed functional groups in the midsouthern United States (Haramoto and Gallandt 2004; Weston 1996).

Interactions with CC-Term timing showed pronounced differentiation against no-till controls versus constrained variation against tilled controls (Derpsch et al. 2014). Regarding CC type, grass-legume mixtures provided stronger suppression relative to tilled baselines, while brassica efficacy remains marginal, modulated by control plot weed dynamics. Grass-legume mixtures, which are known for their high biomass and diversity, typically yield more effective weed suppression (Essman et al. 2023; Kumari et al. 2024; MacLaren et al. 2019; Wortman et al. 2013). Research indicates that brassica CCs decompose rapidly and often exhibit inconsistent allelopathic effects, limiting their effectiveness in long-term weed suppression (Mennan and Ngouajio 2012). Although brassicas produce allelochemicals such as glucosinolates, which can deter weed growth, their rapid degradation results in less prolonged weed inhibition than more robust mixtures (Haring and Hanson 2022). Weed FG and crop type variations denote species-specific agroecological responses (Buhler 1995; Sosnoskie et al. 2006). Sedges in particular exhibit a reduced responsiveness to suppression in undisturbed no-till environments, suggesting that these systems favor certain weed species over others in the absence of mechanical disturbance (Cordeau et al. 2015; Menalled et al. 2022). it's the relatively slow canopy development of cotton and limited early-season shading likely reduce its capacity to synergize with CC residue, particularly in tilled systems where initial weed pressure is already mechanically reduced. Reeves et al. (2005) observed that winter CC systems provided early season weed control and also noted that this benefit may be diminished if cotton's canopy remains underdeveloped, which would limit shading and competitive suppression. These findings emphasize the imperative of considering the tillage context, where inherent weed control from tillage can mask or diminish the observable contribution of CCs.

### Cover Crop-Term Time/Timing

Cover crop termination timing exerted a significant effect on weed suppression effect sizes ($F_{5,22} = 12.42$, $P < 0.001$), accompanied by pronounced residual heterogeneity ($I^2 = 94.4\%$, $P < 0.001$). Variance components revealed substantial contributions from TS-NCC ($I^2 = 25.0\%$), WC-Eval timing ($I^2 = 18.7\%$), CC type ($I^2 = 20.5\%$), and Weed FG ($I^2 = 27.4\%$). Nonterminated CCs had the highest effect size (MD = 57; CI, 7–107; $k = 38$), albeit with marked variability, while all the terminated CCs exhibited significant effects across timings: 0–1 WBP (MD = 28; CI, 15–40; $k = 76$), 2–3 WBP (MD = 37; CI, 25–50; $k = 373$), 4–5 WBP (MD = 38; CI, 26–51; $k = 153$), and ≥6 WBP (MD = 31; CI, 19–44;

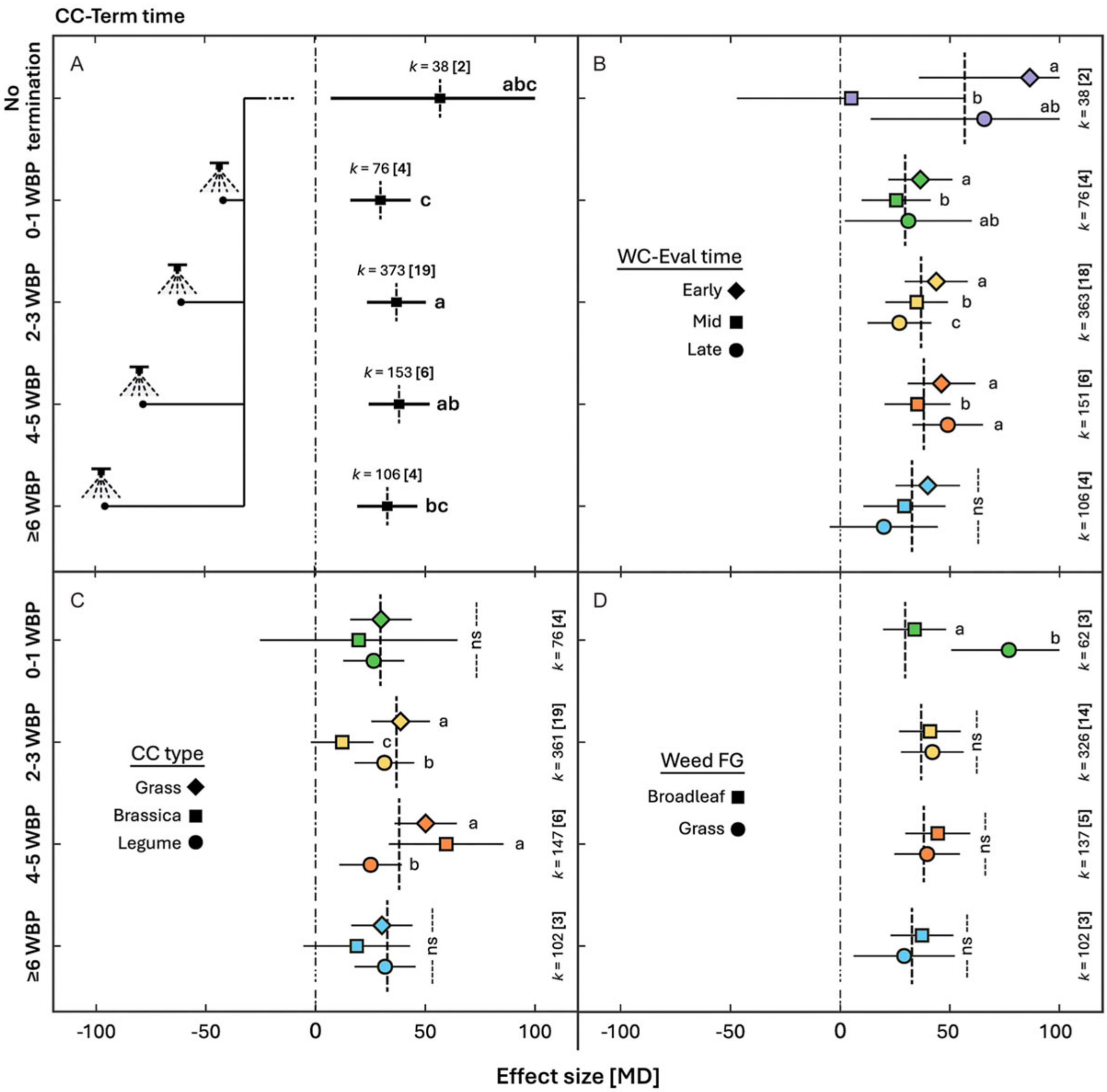


**Figure 3.** Effect sizes (MD) for weed suppression across CC-Term time and interactions. (A) Main effect of CC-Term time. (B) Interaction between CC-Term time and WC-Eval time. (C) Interaction between CC-Term time and CC type. (D) Interaction between CC-Term time and Weed FG. Solid horizontal bars represent CI, dotted vertical lines represent the main effects of the primary moderator. Letters denote significant within-group differences (P < 0.05). CIs were truncated at ±100% for interpretability. Abbreviations: CC-Term time, cover crop termination timing; CC type, cover crop type; CI, 95% confidence interval; *k*, number of effect sizes included for each group; MD, mean difference; WBP, weeks before planting; WC-Eval time, weed control evaluation timing; Weed FG, weed functional group. Numbers in brackets represent the number of publications from which the data originated.

$k = 106$), with fairly constrained variation among termination intervals (Figure 3A).

Interactions between CC-Term timing and WC-Eval timing significantly modulated effect sizes ($\chi^2(8) = 386.53$, $P < 0.001$), with persistent residual heterogeneity ($I^2 = 94.1\%$). Early season WC-Eval timing consistently amplified effects relative to CC-Term timing means (e.g., 4–5 WBP: MD = 45; CI, 32–57; $k = 54$; nonterminated: MD = 86; CI, 73–98; $k = 4$), whereas mid-season effects closely aligned with means (e.g., 4–5 WBP: MD = 35; CI, 22–47; $k = 12$) except for nonterminated CCs, which were nonsignificant (MD = 5; CI, −46 to 55; $k = 4$) (Figure 3B). Late-season evaluation at ≥6 WBP yielded a nonsignificant effect (MD = 19; CI, −5 to 43; $k = 48$). Interactions with CC type ($\chi^2(6) = 67.75$, $P < 0.001$) and Weed FG ($\chi^2(3) = 16.91$, $P < 0.001$) were significant, reducing heterogeneity modestly for CC type ($I^2 = 93.1\%$) and notably for Weed FG ($I^2 = 91.9\%$), whereas crop type interaction was nonsignificant ($\chi^2(3) = 2.93$, $P = 0.402$). Brassica CCs at 0–1 WBP and ≥6 WBP exhibited significant effects (e.g., $MD_{0-1\ WBP} = 20$; CI, −2 to 42; $k = 46$; $MD_{\geq 6\ WBP} = 19$; CI, −4 to 41; $k = 18$), with grass CCs prevailing at 4–5 WBP (MD = 51; CI, 39–64; $k = 85$) (Figure 3C). Weed FG interaction at 0–1 WBP amplified grass weed suppression (MD = 76; CI, 48–104; $k = 11$) over broadleaf weeds (Figure 3D).

Cover crop termination or no termination affected weed suppression level, with nonterminated CCs achieving maximal effects, albeit with variability attributable to sustained weed competition (Ranaivoson et al. 2017; Reberg-Horton et al. 2012) as well as limited paired comparisons. Across the terminated CCs, the constrained variation delineates a broad operational range (Creamer et al. 1996; Weston and Duke 2003). However,

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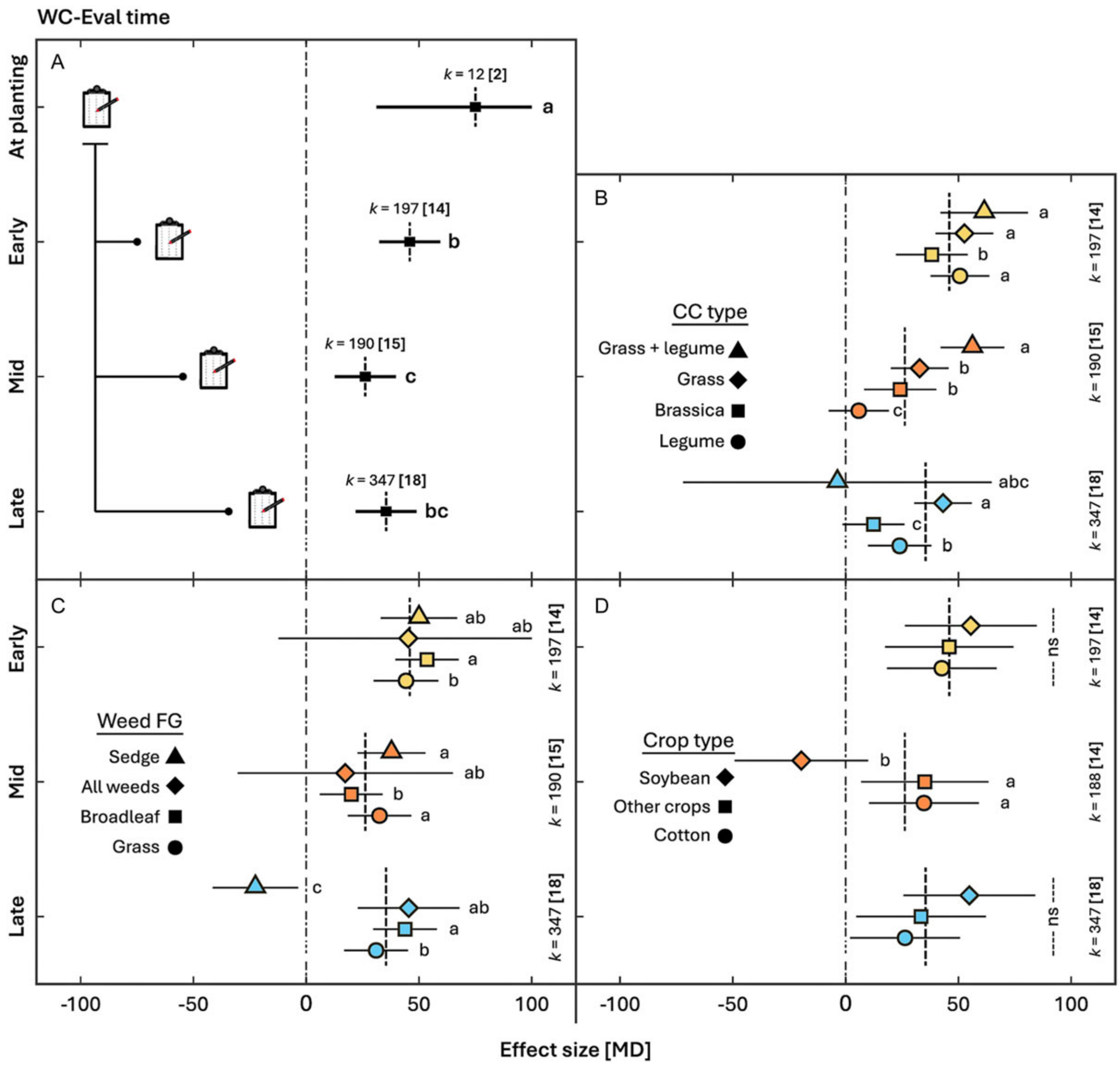


**Figure 4.** Effect sizes (MD) across WC-Eval time and interactions. (A) Main effect of WC-Eval time. (B) Interaction between WC-Eval time and CC type. (C) Interaction between WC-Eval time and Weed FG. (D) Interaction between WC-Eval time and crop type. Solid horizontal bars represent CI, dotted vertical lines represent the main effects of the primary moderator. Letters denote significant within-group differences (P < 0.05). CIs were truncated at ±100% for interpretability. Abbreviations: CC type, cover crop type; CI, 95% confidence interval; *k*, number of effect sizes included for each group; MD, mean difference; WC-Eval time, weed control evaluation timing; Weed FG, weed functional group. Numbers in brackets represent the number of publications from which the data originated.

interactions with WC-Eval timing and CC type reveal temporal and compositional specificity: early termination sustains grass CC efficacy, while brassicas exhibit diminished performance across termination timings, reflecting accelerated residue decomposition (Mirsky et al. 2011; Teasdale and Mohler 2000; Thiessen Martens et al. 2001). This contrasts with temperate regions, where slower decomposition rates allow residues to persist longer, providing extended weed control (Nichols et al. 2020). Differentiated Weed FG responses, particularly when a CC was terminated close to planting, reinforce species-specific functional traits. The absence of crop type interaction supports broad applicability, yet persistent heterogeneity highlights subtropical environmental constraints—thermal and hydric regimes—that modulate efficacy beyond management factors.

## *Weed Control Evaluation Time/Timing*

The effect of WC-Eval timing was significant on weed suppression effect sizes ($F_{4,742} = 73.64$, P < 0.001), characterized by substantial residual heterogeneity ($I^2 = 94.5\%$, P < 0.001) and notable contributions from Weed FG ($I^2 = 26.8\%$) and TS-NCC ($I^2 = 23.3\%$) on variances. At planting or preplanting timing elicited the greatest effect size (MD = 76; CI, 31–120; $k = 12$), followed by early season timing (MD = 48; CI, 34–62; $k$ =197), with mid-season (MD = 33; CI, 19–46; $k = 190$) and late-season (MD = 26; CI, 13–40; $k = 347$) timings demonstrating progressively diminished, yet significant, effects (Figure 4A).

Interactions between WC-Eval timing and CC type ($\chi^2(6) = 125.46$, P < 0.001), Weed FG ($\chi^2(6) = 200.47$, P < 0.001), and crop type ($\chi^2(6) = 369.97$, P < 0.001) were statistically robust, yet exerted minimal influence on residual heterogeneity ($I^2 \approx 94.5\%$). For brassica and grass-legume CCs, late-season evaluations showed no significant effects (MD = 10; CI, −3 to 24; $k = 73$ for brassica and MD = −4; CI, −73 to 66; $k = 4$ for grass-legume) (Figure 4B). However, mid-season evaluations revealed a significant effect for grass-legume mixtures (MD = 57; CI, 43–71; $k = 8$), while the legume effect remained nonsignificant (MD = 6;

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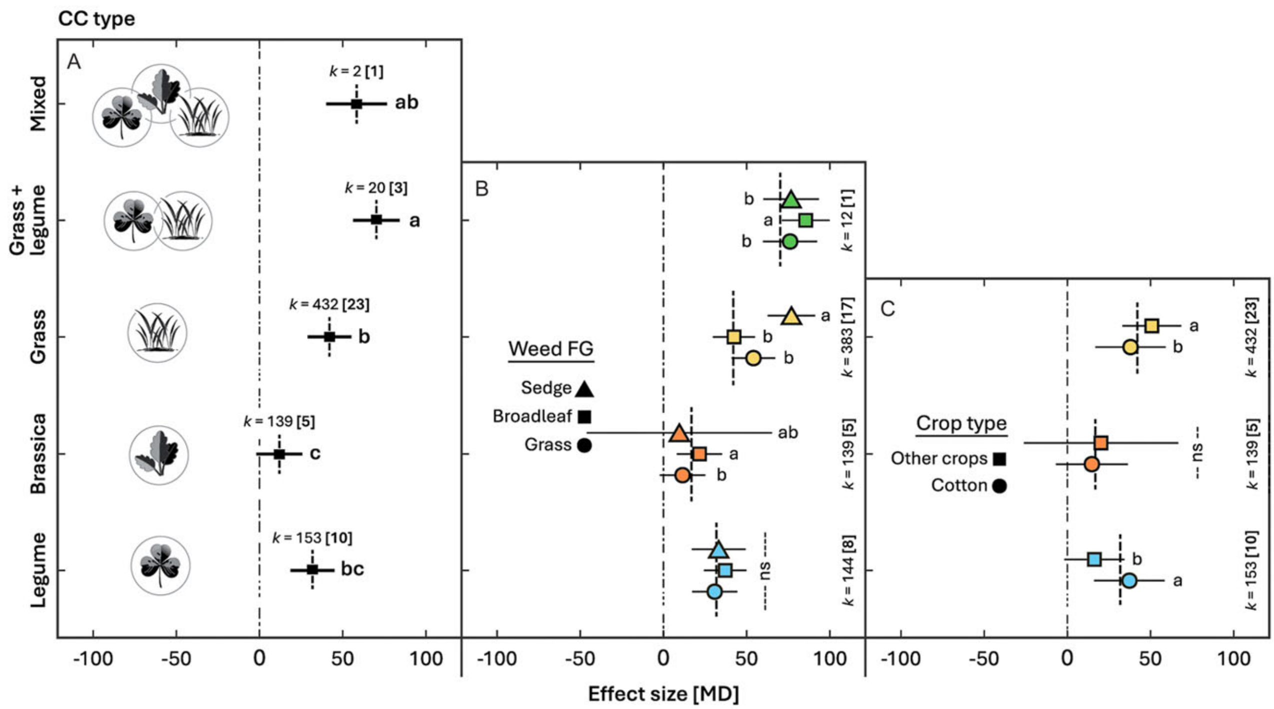


**Figure 5.** Effect sizes (MD) across CC type and interactions. (A) Main effect of CC type. (B) Interaction between CC type and Weed FG. (C) Interaction between CC type and crop type. Solid horizontal bars represent CI, dotted vertical lines represent the main effects of the primary moderator. Letters denote significant within-group differences ($P < 0.05$). CIs were truncated at ±100% for interpretability. Abbreviations: CC type, cover crop type; CI, 95% confidence interval; *k*, number of effect sizes included for each group; MD, mean difference; Weed FG, weed functional group. Numbers in brackets represent the number of publications from which the data originated.

CI, −7 to 19; $k = 48$). Early season effects exhibited limited differentiation across CC types. Weed FG effects remained consistent across timings, except for a notable late-season decline for sedge weeds (MD = −24; CI, −43 to −5; $k = 7$) (Figure 4C). Crop type effects were stable in early and late-season timings, but mid-season soybean suppression was nonsignificant (MD = −21; CI, −51 to 9; $k = 22$) (Figure 4D).

Weed control evaluation timing constitutes an important determinant of weed suppression, with at planting or preplanting timing achieving maximal effect attributable to optimal residue-mediated interference with weed emergence. Subsequent mid- and late-season reductions in the suppression levels reflect accelerated residue decomposition under the warm, humid subtropical conditions in the midsouthern United States (Reberg-Horton et al. 2012; Smith et al. 2011). Interactions with CC type delineate temporal specificity, with grass-legume mixtures sustaining elevated suppression mid-season, contrasting with late-season loss of weed suppression by brassicas due to rapid residue degradation (Finney et al. 2016). Weed FG stability, barring late-season sedge sensitivity, indicates differential ecological responses to timing, potentially linked to light and moisture dependencies (Bàrberi and Mazzoncini 2001). Crop type variations, notably the mid-season suppression failure of soybean, point to competitive interactions modulated by residue persistence and crop growth. Persistent heterogeneity highlights the primacy of management factors and subtropical environmental drivers in shaping outcomes.

### Cover Crop Type

Cover crop type had a notable effect on weed suppression effect sizes ($F_{5,741} = 83.96$, $P < 0.001$), accompanied by high residual heterogeneity ($I^2 = 94.4\%$, $P < 0.001$). Variance components revealed substantial contributions across multiple factors, notably Weed FG ($I^2 = 32.5\%$) and TS-NCC ($I^2 = 23.9\%$). Grass-legume mixtures had the most pronounced effect (MD = 70; CI, 56–84; $k = 20$), followed closely by mixed CCs (MD = 58; CI, 40–76; $k = 2$), whereas brassica CCs demonstrated a nonsignificant effect (MD = 13; CI, 0–27; $k = 139$) (Figure 5A).

Interactions between CC type and Weed FG ($\chi^2(6) = 105.55$, $P < 0.001$) and crop type ($\chi^2(2) = 150.22$, $P < 0.001$) were significant, with Weed FG uniquely reducing residual heterogeneity in interaction models ($I^2 = 91.94\%$). Grass CCs markedly elevated efficacy against sedges (MD = 80; CI, 65–94; $k = 11$) relative to broadleaf (MD = 45; CI, 31–58; $k = 243$) or grass weeds (MD = 53; CI, 39–66; $k = 129$) (Figure 5B). The effect sizes across Weed FG remained undifferentiated within legume or grass-legume CCs. Brassica CCs suppressed only broadleaf weeds (MD = 18; CI, 5–32; $k = 72$). Grass CCs provided suppression in non-cotton crops (MD = 51; CI, 33–69; $k = 138$), surpassing cotton within this CC category (Figure 5C). However, the outcome was opposite with the legume CCs.

CC type is a key determinant of weed suppression efficacy. Grass-legume mixtures (e.g., cereal rye-hairy vetch) are particularly effective due to their synergistic biomass accumulation and complementary allelopathic properties (Brennan and Smith 2005; Haramoto and Gallandt 2004), whereas brassicas (e.g., radish) exhibit limited persistence under midsouthern conditions due to rapid residue breakdown (Keene et al. 2017; Smith et al. 2020). This performance gradient underscores how biomass-driven suppression is mediated by climate-specific decomposition rates, which disproportionately reduce the efficacy of low-C:N residues (e.g., legumes, brassicas) in subtropical systems (Bunchek et al. 2020; Mirsky et al. 2011). Interactions with Weed FG—exemplified by

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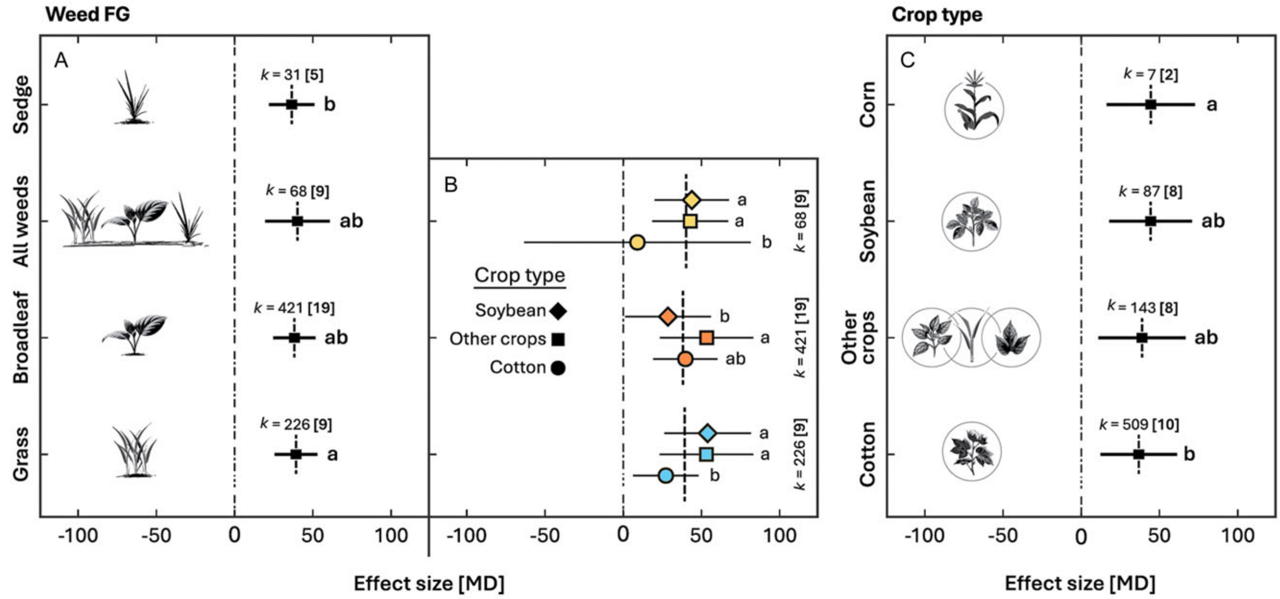


**Figure 6.** Effect sizes (MD) across Weed FG and crop type. (A) Main effect of Weed FG. (B) Interaction between Weed FG and crop type. (C) Main effect of crop type. Solid horizontal bars represent CI, dotted vertical lines represent the main effects of the primary moderator. Letters denote significant within-group differences (P < 0.05). Abbreviations: CI, 95% confidence interval; *k*, number of effect sizes included for each group; MD, mean difference; Weed FG, weed functional group. Numbers in brackets represent the number of publications from which the data originated.

the pronounced suppression of sedges by grass CCs—suggest species-specific ecological mechanisms, potentially mediated by root exudates or canopy shading (Kruidhof et al. 2009). Crop-type effects, such as enhanced suppression in non-cotton systems with grass CCs, reflect agronomic compatibility modulating outcomes (Reddy 2001). Persistent heterogeneity indicates the role of unaccounted variables for the outcomes.

### Weed Functional Group and Crop Type

The Weed FG showed significant yet modest effects on weed suppression ($F_{4,29} = 9.84$, P < 0.001), with MDs ranging narrowly from 37 for sedge weeds (CI, 22–51; $k = 31$) to 40 for the "all weeds" category (CI, 19–61; $k = 68$), all with P < 0.001 (Figure 6A). High residual heterogeneity ($I^2 = 93.7\%$, P < 0.001) and pronounced variance components—notably for TS-NCC ($I^2 = 27.6\%$) and CC type ($I^2 = 25\%$)—reveal the predominance of extraneous factors. The interaction between Weed FG and crop type was significant ($\chi^2(4) = 67$, P < 0.001), manifesting differential effect sizes across crop types within each Weed FG, with cotton often showing lower suppression relative to non-cotton crops (Figure 6B). Crop type also had an impact on effect sizes ($F_{4,23} = 6.71$, P = 0.001), with MDs spanning 34 for cotton (CI, 10–58; $k = 509$) to 42 for corn (CI: 14–70; $k = 7$), each significant (P < 0.012). However, the constrained range of variation suggests a limited moderating power. Uniquely high residual heterogeneity ($I^2 = 95.3\%$, P < 0.001), coupled with variance contributions such as Weed FG ($I^2 = 24\%$), indicate that management factors exert primary control over suppression outcomes.

Collectively, Weed FG and crop type contribute modest effects to weed suppression. Their influence is subsidiary to dominant management variables such as tillage regime and CC type. Differential crop-CC interactions—particularly the reduced grass weed suppression observed in cotton systems—highlight competitive and allelopathic disparities, with non-cotton crops (e.g., corn, soybean) exhibiting more consistent suppression efficacy. This variability is driven by cotton's slow early growth and limited shading capacity, which fails to complement CC residues (Balkcom et al. 2015). Elevated heterogeneity in weed suppression linked to TS-NCC and CC type further underscores the agroecological complexity of these interactions, where soil temperature, residue persistence, and cash crop synchrony modulate outcomes (Nichols et al. 2020; Teasdale and Mohler 2000).

This meta-analysis establishes that CC-mediated weed suppression in the midsouthern United States is governed by a multifaceted nexus of factors—TS-NCC, CC-Term timing, WC-Eval timing, CC type, Weed FG, and crop type—highlighting the limitations of univariate analyses in resolving management-specific outcomes (Nichols et al. 2020; Pittelkow et al. 2015). The tillage regime of control plots critically dictates effect sizes: no-till controls, with elevated baseline weed pressure, enhance CC suppression, whereas tilled controls, leveraging mechanical weed abatement, diminish apparent efficacy—a distinction pivotal to interpreting regional performance (Reberg-Horton et al. 2012). CC-Term timing modulates this further, with nonterminated CCs eliciting pronounced early season suppression, attenuated by accelerated residue decomposition under subtropical conditions, in contrast to consistent effects across terminated intervals (Snapp et al. 2005). WC-Eval timing exhibits analogous temporality, with maximal suppression at early stages declining as residue persistence wanes. CC type exerts a determinative role, with grass-legume mixtures demonstrating superior suppression via biomass accumulation and adaptability, whereas brassicas exhibit diminished efficacy due to rapid degradation and variable control (Haramoto and Gallandt 2004; Tosti et al. 2014). Weed FG and crop type impart secondary, yet statistically significant, contributions that are intricately linked to primary management variables. Robust two-way interactions and associated high heterogeneity affirm a context-specificity irreducible to generalized models.

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Effect sizes across analyses consistently indicate positive weed suppression, validating the use of CCs as a dependable strategy in the midsouthern United States However, the omission of CC biomass as a covariate (Bunchek et al. 2020; Wallace et al. 2019) and crop yield as an outcome metric (Finney et al. 2016; Nord et al. 2011; Peng et al. 2024) restricts both mechanistic understanding and comprehensive agronomic evaluation. The subtropical environment in the midsouthern United States, which is characterized by high temperatures, humidity, and sustained weed pressure, accelerates residue decomposition and alters weed suppression dynamics compared to temperate systems, necessitating region-specific management approaches (Keene et al. 2017; Mirsky et al. 2011). Persistent residual heterogeneity across models denotes unaccounted variables—such as soil microbial activity, microclimatic variation, or weed seedbank status that modulate CC efficacy beyond the moderators assessed here, thereby delineating prospects for refined management optimization (MacLaren et al. 2019). These findings also substantiate the necessity of integrated management frameworks over isolated factor analyses for optimizing CC-mediated weed suppression in midsouthern cropping systems.

This meta-analysis demonstrates that CCs provide consistent but context-dependent weed suppression across midsouthern U.S. cropping systems ($I^2 > 90\%$). Two key findings emerge: 1) grass-legume mixtures outperform monocultures, particularly in no-till systems; and 2) suppression is most pronounced during early weed emergence. While the results confirm CC value for weed management, two knowledge gaps may limit practical implementation: 1) the lack of biomass data prevents quantification of CC biomass-weed suppression relationships; and 2) absent yield metrics constrain economic assessments. Future metanalyses should consider these measurements with weed suppression evaluations to optimize region-specific recommendations that balance agronomic and economic outcomes.

## Practical Implications

This synthesis provides critical insights for diverse stakeholders navigating CC adoption in the midsouthern United States. For growers, the superiority of grass-legume mixtures over monocultures, particularly in no-till systems, offers clear guidance for species selection, while the window of effectiveness provides practical operational flexibility for weed suppression outcome. The consistent early season weed suppression underscores the role that CCs play in managing initial weed flushes, complementing existing control methods. Researchers will find significant value in the revealed context-specific patterns to further target investigations for refining management protocols. Policymakers can leverage robust evidence of the weed suppression benefits of CCs to justify expanded support programs, especially in no-till agriculture. Collectively, these findings establish an empirical foundation for advancing CC adoption as part of integrated weed management systems, with particular relevance for addressing herbicide resistance challenges in the region.

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