**Target Journal:** Agricultural and Environmental Letters

**Title:**

How do cover-crops effect weeds in the US Corn Belt? A meta-analysis

Is it feasible to replace traditional weed-control methods with cover-crops in the US Corn Belt?

Cover-crops reduce weed biomass in Midwestern maize-based systems

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**Core ideas (85 characters for each bullet, 3-5 bullets)**

* Cover-crops reduced weed biomass, but not weed density
* Grass monocultures are the most weed suppressive cover-crop
* 5 Mg ha-1 of cover-crop residue was required to reduce weed biomass by 75%
* Achieving 5 Mg ha-1 requires planting cover-crops before typical crop harvest dates
* Maximizing yield benefits and weed suppression from cover-crops may not have over-lapping strategies

**Abstract (<150 words)**

Interest in winter cover-crops (CCs) in the Midwestern United States has increased steadily over the past decade. In addition to soil conservation benefits, CCs may offer weed control, but individual studies in this region report varying effects. We conducted a meta-analysis of studies measuring weed biomass (WBIO) or density (WDEN) in paired CC and no-cover treatments in maize (*Zea mays*)-soybean (*Glycine max*) rotations in the Midwest. Fifteen studies met our criteria, resulting in 123 paired comparisons of WBIO and 119 of WDEN. Grass CCs significantly reduced WBIO, while no CC type reduced WDEN. We found no evidence management factors (e.g. planting method) directly impacted outcomes. Higher CC biomass was associated with more weed control, and a 75% reduction in WBIO required 5 Mg ha-1 of CC. Ancillary use of a process-based model (SALUS) demonstrated achieving 5 Mg ha-1 requires substantially delayed termination in most years. We conclude CCs significantly reduce WBIO, but CCs alone cannot consistently control weeds in this region.

**Abbreviations**

Cover-crop (CC)

Weed biomass (WBIO)

Weed density (WDEN)

Cover-crop biomass (CCBIO)

United States (US)

System Approach to Land Use Sustainability (SALUS)

Midwestern region of the United States (Midwest)

**Introduction**

Winter annual cover-cropping has been heavily promoted in the Midwestern region of the United States (Midwest) due to an increasing need for practices that improve soil and water quality. Despite clear environmental benefits (Kaspar and Singer, 2011; Daryanto et al., 2018), only a small fraction of Midwest cropland is currently managed with CCs (Seifert et al., 2018). Benefits from growing CCs are not easily monetizable to farmers in the short term, creating a major barrier to adoption (Plastina et al., 2018; Roesch-Mcnally et al., 2018). The ability of CCs to replace other weed management costs could provide immediate monetary incentives for adoption. While other reviews on CC-weed interactions are available, the maize (*Zea mays*)-soybean (*Glycine max*) system ubiquitous in the Midwest merits explicit consideration, as context-specific analyses offer insights precluded by global-scopes. Conditions in the Midwest are known to limit CC establishment and biomass production (Strock et al., 2004; Baker and Griffis, 2009), which in turn may affect factors governing CC performance relative to weed management. Region-specific analyses can also provide more precise CC biomass (CCBIO) production targets for weed suppression and explore how early-planting or late-termination affect the feasibility of achieving these targets.

To address these research gaps, we synthesized data from published field studies measuring weed responses to CCing in maize-soybean systems in the Midwest. Our objectives were to (1) quantify how environmental and managerial factors affect weed responses to CCing, (2) identify Midwest-specific CCBIO targets for providing significant weed suppression; and (3) evaluate the feasibility of achieving these targets under various planting/termination scenarios. Answers to these questions provide a basis for designing effective and feasible CC-facilitated weed-control in the Midwest, which in turn could incentivize their use and result in improved environmental quality for the region.

**Methods**

**Meta-analysis of weed-responses to cover-cropping**

We conducted a systematic search of literature using ISI Web of Knowledge (WoS,

available online) Core Collection and CAB Direct databases. Search details are in supplementary text, including a PRISMA diagram and list of included publications (**S1**). We included WBIO, WDEN, and cash-crop yield as response variables in our database. Values were recorded in a paired format, requiring the response variable to be measured in the same crop at the same time with all aspects of management held constant except for a treatment of a fall-planted CC. Ancillary data included geographical location, climate, and soil characteristics of the study site; cash- and CC-management including species, tillage system, planting and termination methods and dates; and experimental information such as timing of weed measurements and type of weed (**Table S1**). The complete database is published and available on Iowa State University’s DataShare platform (**CITE**).

All data manipulation and statistical modelling were done in R version 3.6.1 (R Core Team,) using the tidyverse meta-package (Wickham et al., 2019) and others (Grolemund and Wickham, 2011; Firke, 2019). A detailed account of statistical methods is presented in supplementary material (**S2**), and all R code is available on github (**it will be once this is accepted for publication**). In brief, all statistical models used the log-transformed response ratio (measurement in the CC-treatment over measurement in the no-cover treatment) as the response variable (Gurevitch et al., 2018). Mixed-effect models were used with the modifier of interest as a fixed effect and a random intercept for each study using non-parametric weighting based on the number of replicates (Adams et al., 1997). All linear models were fit using the lme4 package (Bates et al., 2015), and results were analyzed using lmerTest (Kuznetsova et al., 2017) and emmeans (Lenth et al., 2018). To identify suites of practices predictive of achieving both a reduction in weeds and an increase in cash-crop yield with CCing, we fit random forest models (Kuhn and Johnson, 2013) using several R packages (Hothorn et al., 2006). All statistical results can be found in the supplementary materials (**S3**).

**Simulation of rye cover- crop biomass**

To investigate where it is feasible to manage CCs for effective weed control in the Midwest, we used the System Approach to Land Use Sustainability (SALUS) model (Basso and Ritchie, 2015) to simulate winter rye (*Secale cereal*) biomass across a range of soils and weather conditions in the area. Rye is the most prevalent CC species used in the Midwest (Singer, 2008) and represents the most optimistic choice for maximizing CCBIO production in this region (Appelgate et al., 2017; Ruis et al., 2019). Details about simulations are provided in supplementary text (**S4**).

**Results and Discussion**

**Meta-analysis results**

Fifteen articles fit our criteria, producing 123 response ratios for WBIO and 119 response ratios for WDEN (**CITE our data**). The studies include a range of site characteristics and management representative of Midwestern maize-soybean production systems (**Table S1**). Overall, CCs significantly reduced WBIO (p=0.02), which was robust against publication bias (>3000 unpublished null-studies needed; Rosenthral 1979) and the removal of individual studies (p-values ranged from 0.01-0.04). There was no evidence CCs reduced WDEN (p=0.98). Neither WBIO nor WDEN responses were affected by the subsequent cash-crop (maize or soybean), meaning the response of weeds to CCing was not confounded by differences in cash-crop competition with weeds.

The following categorical modifiers had levels with significantly different effects on WBIO (**Fig. 1A**): CC type (after controlling for CCBIO production; grass, other), measurement in reference to cash-crop planting (before, after), and weed growth habit (winter annual, summer annual, perennial). WDEN had no significant modifiers.

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| **Figure 1** **(A)** Variables with significantly different level effects; values less than 0 (dotted line) indicate cover-crops reduced weeds, large red points indicate significant effects (p<0.05) with estimates transformed to percent, n values indicate number of observations for the estimate, error bars are 95% confidence intervals **(B)** Comparisons where cover-crops increased cash-crop yields and reduced weed biomass (circles) or density (triangles) made up 23% of the points (gray quadrant)  \*After controlling for cover-crop biomass production |

For WBIO, grass CCs reduced WBIO by 68% compared to a non-significant reduction of 33% for other CCs (p<0.01; Fig. 1B). Measurements taken before cash-crop planting showed a 74% reduction in WBIO, compared to only 44% in measurements taken after planting (p<0.01). Winter annual weeds showed the largest reductions (65%), followed by summer annuals (47%), with perennial weeds being unaffected by CCs. For continuous variables, weed suppression was significantly affected by CCBIO for both WBIO (p=0.03) and WDEN (p<0.01). WBIO was negatively associated with CCBIO regardless of CC type. We found an estimated 5 Mg ha-1 of CCBIO at termination reduced WBIO by 75% for grass CCs, but only 40% for other CCs.

The response of WBIO/WDEN to CCing did not depend on any other modifiers tested. A full list of non-significant modifiers can be found in supplemental material and included production system tillage regime; CC planting/termination method; termination-planting gap; study-site latitude, aridity, and soil type.

In our database only 23% of the comparisons exhibited a ‘win-win’ situation, with a concomitant increase in cash-crop yield and decrease in weed pressure (**Fig. 1B**). Using a random forest model, we found no scenarios that were strong predictors of whether an observation would fall in the win-win category, suggesting maximizing cash-crop yields and weed suppression may not have overlapping management strategies.

**Process-based model simulation results**

For the realistic (Oct-7) planting date, only 2% of counties achieved 5 Mg ha-1 by May-1 in 80% of the weather-years. For the optimistic (Sep-15) CC-planting date, this increases to only 30% (**Fig. 2B**). With late planting (Nov-1), none of the counties reached the threshold by May-1, and only half did so by Jul-1. Aggregated on a state-level, Illinois, Missouri, and Kansas were the only states that could consistently achieve 5 Mg ha-1 of biomass before typical cash-crop planting dates of early May (**Fig. 2A**).

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| **Figure 2.** Earliest termination date with rye (*Secale cereal*) biomass in excess of 5 Mg ha-1 as predicted by the SALUS crop model using 30 years of historical weather for three rye planting date scenarios (Sep-15, Oct-7, Nov-1). Results in **(A)** are summarized by state at 80% probability levels. In Iowa, for example, rye biomass was greater than 5 Mg ha-1 in 80% of the years, if planted on Oct-7 and terminated on or after Jun-17 (highlighted in red). Results in **(B)** correspond to the Oct-7 planting scenario, summarized by county at the 80% probability level**.** |

**Discussion**

Cover crops can both inhibit (lower light, lower soil temperatures, smaller ranges in temperatures, lower soil nitrate concentrations, allelopathic chemicals) and stimulate (increased soil moisture, protection from desiccation, protection from export via erosion) weed seed germination, and the net effect will vary by year, as evidenced by the inconsistent effect of CCing on WDEN. Conversely, the suppressive effects of CCs on WBIO (increased resource competition, delayed germination) are less contextual, and therefore show a stronger, more consistent reduction. Smaller weeds are more susceptible to other forms of weed control (Wallace et al., 2019), but long-term (>5 years) studies are needed to understand if repeated reductions in WBIO from CC-use can translate into reduced WDENs over time.

Even after controlling for the effect of CCBIO, monocultures of grass CCs offered significant suppression of WBIO (reduced by 68%), while other CCs did not (**Fig. 1A**), consistent with recent studies (MacLaren et al., 2019; Smith et al., 2020). Cover-crop induced control is a combination of physical and chemical suppression, and grasses such as rye may be more effective than legumes and brassicas on both fronts (Creamer et al., 1996; Smith et al., 2020). The carbon-to-nitrogen ratio of grass CCs can be twice as high as legumes (Quemada and Cabrera, 1995; Martinez-Feria et al., 2019), potentially increasing residence time of the residue and thus suppressing weeds longer after CC termination (Teasdale and Mohler, 1993; Ruffo and Bollero, 2003). Rye residue also exhibits an allelopathic effect, which can both inhibit weed seed germination and reduce WBIO (Dhima et al. 2006; Teasdale et al. 2012).

While CC had a stronger effect on weeds before cash-crop planting (**Fig. 1A**), weeds measured after planting are likely of more interest to producers, as they directly represent resource competition with the cash-crop. The stronger reduction in winter annual weeds is un-surprising, given the winter growth period of the CC. In our database the tillage regime of the system did not affect CC weed suppression (p = 0.13), meaning although CCs and no-till demonstrate synergies for soil improvements (Basche and DeLonge, 2019), we found no evidence of synergistic weed control. The environmental context of the studies had no significant effect on the weed responses nor the CCBIO productions. This could simply reflect the lack of measurement/reporting plot specific information (Gerstner et al., 2017; Eagle et al., 2017), but our results suggest the environmental context has an indirect effect on CC-mediated weed suppression, while CC type and CCBIO production have direct effects.

To prevent an increase in weed seedbanks, reductions in WDEN of 90% (comparable to herbicide effectiveness) are needed (Liebman and Nichols, 2020), and our study shows even with 5 Mg ha-1 of grass CCBIO, producers are unlikely to achieve this level of weed control, consistent with studies from other areas (Mirsky et al., 2013; Baraibar et al., 2018). Futhermore, our SALUS simulations indicate achieving 5 Mg ha-1 of rye CCBIO regularly under typical US Midwest production scenarios and climates would be challenging (**Fig. 2**). Even with optimistic CC planting dates (Sep-15), achieving 5 Mg ha-1 of CCBIO would require a mid-May or later termination date most of the years (80%) in most counties. A more realistic CC planting date (Oct-7) requires termination dates in late-May and June for most of the Midwest, well after typical cash-crop planting dates. In maize, delayed planting consistently reduces yield (Bollero and Bullock 1994; Baum et al. 2019). For soybean, planting dates are less crucial (Egli and Cornelius 2009; Kessler et al. 2020), but some conservation districts require CC termination gaps before cash-crop planting to remain eligible for subsidized crop insurance (**CITE**), limiting the use of delayed termination to maximize weed control from CCs. Fertilization could increase CCBIO but would result in an additional cost and may negate other environmental services. Early fall planting may therefore be the best option for increasing CCBIO and therefore weed suppression. While aerial seeding can be used to establish CCs into standing crops, these methods are often unreliable (Wilson et al., 2014), and standing crops prevent full sunlight penetration for CC growth well into October. Further, it should be noted our simulations assumed direct seeding with uniform germination (**S4**) and should therefore not be extrapolated to other planting methods. Other ecosystem services of CCs increase with CCBIO (Blanco-Canqui et al., 2015; Thapa et al., 2018), signifying a common goal for Midwestern CC researchers.

Other studies have looked specifically at the effects of CCs on subsequent cash-crop yields (Marcillo and Miguez, 2017), showing no yield benefit from grass CCs, and yield increases with legumes and mixes that was enhanced in no-till. In contrast, our study found no evidence mixes and legumes suppress weeds and saw no additional weed suppression in no-till. Choosing a CC species to maximize cash-crop yields versus weed suppression may be at odds, and while no-till may amplify yield responses it may not enhance weed control from CCs. The existence of these tradeoffs is supported by the low percentage of observations with a ‘win-win’ scenario (**Fig. 1B**) in our database.

**Conclusions**

Our study, which specifically targeted the maize-soybean rotation ubiquitous in the Midwest, shows grass CCs significantly reduce WBIO but has inconsistent effects on WDEN, with no evidence other types of CCs reduce either. We estimated 5 Mg ha-1 of grass CCBIO reduces WBIO by 75%, but consistently achieving that level of CCBIO in the Midwest may not be feasible within the traditional maize/soybean fallow season. Furthermore, concomitant increases in yields and decreases in weeds with the use of CCs only occurred in 25% of the cases, suggesting although CCs reduce WBIO, this doesn’t necessarily translate to increased yields. Therefore, we conclude that although CCs significantly reduce WBIO, which may render other weed managements more effective, achieving consistent weed control in this region from CCs would be challenging.

**Supplemental Material statement**

All supplementary files are available as a PDF accompanying this manuscript.

**Data Availability statement**

All data associated with this analysis has been published (**CITE**) and is publicly available at **XXonce it’s acceptedXX**. Additionally, the data is available as an R package on github, and all R code used to analyze the data is available in a github repository (**XXonce it’s acceptedXX**).

**Conflict of Interest statement**

The authors declare they have no conflict of interest

**Acknowledgments**

We’d like to acknowledge Alisha Bower and **ANDREA YOUR HELPER** who assisted with literature searches, Stefan Gailans who provided helpful feedback, Megan O’Donnell who assisted with dataset publication, and Katherine Goode who provided statistical advice.

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