**Target Journal:** Agricultural and Environmental Letters

**Title:** Are cover-crops effective weed control 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 US

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

* Grass cover-crops reduced weed biomass, but not weed density
* Legume cover-crops had no effect on weeds
* 5 Mg ha-1 of cover-crop residue was required to reduce weed biomass by 75%
* There is low probability of achieving 5 Mg ha-1 in a typical Midwestern winter shoulder season
* Grass cover-crops cannot reliably replace other forms of weed control
* Abstract
* Abbreviations
* Text
* Supplemental Material statement
* Data Availability statement(optional)
* Conflict of Interest statement
* Author Contributions statement (optional)
* Acknowledgments (optional)
* References list
* Figure captions
* Tables\*
* Figures\* (figures may also be submitted separately as high-resolution image files in the following acceptable formats: EPS, TIF, PDF, or JPEG)

**Abstract (<150 words)**

Interest in winter annual 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, but not 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 this amount of CC biomass 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)

United States (US)

(SALUS)

Midwestern region of the United States (Midwest)

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**(<2500 words, figs/tables count as 300 words) (2 figs: 600 words, 1900 text words available)**

**Intro (500) less**

**M&M (500) need less**

**Results (500)**

**Discussion (500)**

**Conclusion (100)**

**Introduction (currently 342 words)**

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; Blanco-Canqui et al. 2015; Basche and DeLonge 2019), 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, which creates a major barrier to adoption (Roesch-Mcnally et al., 2018)(Plastina et al. 2018). The ability of CCs to replace other weed management costs could provide immediate monetary incentives for adoption. Cover-crops are a component of integrated weed management (Teasdale 1996; Liebman et al. 1997), help combat herbicide-resistance issues (Cholette et al., 2018), and can reduce weed-control costs in other regions (Mischler et al. 2010). 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 (455)**

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 our 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; Bryan and Zhao 2018; 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**).

**3. Results and Discussion**

**3.1 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 (**Fig 1; 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, non-grass), 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 non-grass (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 annuals showed the strongest 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 non-grass 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**

Some Stats for the narrative:

* When planted in 7-Oct and at the 0.8 probability level, only 2% of counties were predicted to reach 5.0 Mg ha-1 by 1-May, and this increased to 37% of the counties by 1-Jun and 76% by 1-Jul.
* In the early planting scenarios, this increased to 31, 71 and 98% for 1-May, 1-Jun and 1-Jul, respectively.
* With late CC planting, none of the counties reached the threshold by 1-May, and only about half (56%) did so by 1-Jul

I used the summary table below:

*Percent of counties with predicted biomass > 5.0 Mg ha at the 80% probability level*

|  |  |  |  |
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| **DOP** | **JUL-1** | **JUN-1** | **MAY-1** |
| **Sep-15** | 97.9% | 70.6% | 30.5% |
| **Oct-7** | 75.8% | 36.9% | 2.2% |
| **Nov-1** | 56.4% | 6.3% | 0.0% |

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**).

Aggregated on a state-level, Illinois, Missouri, and Kansas were the only states that, even with an optimistic planting date, could consistently achieve this amount 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. Simulations were run for three rye planting date scenarios (Sep-15, Oct-7, and Nov-1), each one for 30 years of historical weather. Results in **(A)** are summarized by state at 80% probability levels. In Iowa, for example, rye biomass was greater than 5.0 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**

The different responses of WBIO versus WDEN suggest WDEN responses to CCing are more variable in the Midwest than WBIO. 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. Conversely, the suppressive effects of CCs on WBIO (increased resource competition, delayed germination) are less contextual, and therefore show a stronger, more consistent reduction. Long-term (>5 years) studies are needed to better understand if repeated reductions in WBIO from CC-use can translate into reduced WDENs over time.

Even after controlling for the effect of CCBIO, grass CCs offered significant suppression of WBIO (reduced by 68%), while non-grass CCs did not (**Fig. 1A**). Cover-crop induced control is a combination of physical and chemical suppression, and grasses such as rye may be more effective than legumes 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 annuals 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 = **XX**). A previous meta-analysis found no-till amplified reductions in WDEN associated with cash-crop diversification (Weisberger et al. 2019), but we found no evidence of such synergy in our database. The environmental context of the studies had no significant effect on the weed responses nor the CCBIO productions. This is consistent with other global CC studies (Basche and DeLonge, 2019), and could simply reflect the lack of measurement/reporting plot specific information (Gerstner et al., 2017; Eagle et al., 2017). Our results suggest that the environmental context under which a CC has an indirect affect on 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 weed control comparable to herbicides. Other studies corroborate our findings (Mirsky et al., 2013; Baraibar et al., 2018). 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 in the Midwest 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 more CCBIO (**CITE**), demonstrating a common goal for Midwestern CC researchers.

Assessing whether there is a trade-off in managing CCs for weed control versus yield maintenance is an important, un-answered question. 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 enhance yield responses it may not effect weed responses to CCs. This is supported by the low percentage of observations with a ‘win-win’ scenario (**Fig. 1B**) in our database.

**4. 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 non-grass CCs reduce either. We estimated 5 Mg ha-1 of grass CCBIO reduces WBIO by 75%, but consistently achieving that level of CCBIO in this region may not be feasible within the traditional maize/soybean fallow season. Furthermore, less than 25% of the comparisons had concomitant increases in yields and decreases in weeds with the use of CCs, 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, CCs alone cannot consistently control weeds in this region.

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