**Abstract (219 words right now)**

Incorporation of over-wintering cover crops (CCs) into Midwestern maize-soybean systems offers numerous environmental advantages including decreased nitrate leaching and reduced soil erosion. However, the contribution of CCs to weed control is poorly understood, with wide ranges in study results. Insight into the experimental, environmental, and managerial factors that influence weed responses to CCs in these systems is needed, as CCs could offer short-term benefits to producers by reducing input costs associated with weed control. To address this, we conducted a meta-analysis on studies performed in maize-soybean rotations in the Midwestern grain-producing region of the United States that measured either weed biomass or density in both a CC and no-cover treatment. We found 15 studies that met our criteria, resulting in 123 paired comparisons of weed biomass and 119 of weed density. Higher CC biomass was associated with more weed control, with 4 Mg ha-1 providing 50% reduction in weed biomass and 50% reduction in weed density. Even after accounting for CC biomass production, grass cover crops reduced weeds more compared to non-grasses. Weed suppression from CCs was strongest for winter annuals, intermediate for summer annuals, and had no effect on perennial weeds. No other management factors (termination method, planting method, tillage system, CC termination to cash crop planting gap) were important in determining weed suppression. We found there was no significant trade-off in managing CCs for both weed suppression and yield maintenance. However, managing CCs to achieve maximum weed control may be challenging under the climate and management constraints of a traditional Midwestern maize-soybean system.

**Introduction**

Integrated weed management approaches are becoming more critical as the prevalence of weeds with resitance to multiple modes of herbicide action increases (CITE). Cover crops (CCs) are a potential tool for multi-faceted weed management approaches (CITE). Additionally, they offer myriad long-term environmental benefits in many agricultural production systems (Kaspar and Singer 2011, Blanco-Canqui et al. 2015). In Midwestern maize-based systems they have been found to reduce soil erosion, improve water quality, increase water infiltration (CITE). While long-term benefits have been quantified, there is less research that helps producers identify short-term agronomic benefits of CCs that might help them offset production costs. A recent study showed partial budgets annual net returns to CCs are negative for the majority of Midwestern producers (Plastina et al. 2018). Identifying ways

Recent meta-analyses have shown cash crop diversification (Weisberger et al. 2019) and use of cover crops (Ospitan et al. 2018) can offer weed control in a range of grain production systems. However, maize-soybean systems in the Mid-western United States (US) make up a large percentage of US land-use and have disproportionate impacts on water quality in the Mississippi drainage basin (Jones et al. 2018, CITE). This unique and ubiquitous production system merits specific consideration with regard to weed suppression offered by cover crops, as context-specific analyses can offer insights not accessible through broader analyses. For example, a state-specific synthesis paper found grasses and broadleaf cover crops were equally and significantly weed-suppressive in their production systems (Baraibar et al. 2019), in contrast to results from a world-wide meta-analysis that found grass cover crops were not effective at reducing either weed biomass or density (Ospitan et al. 2018, god that paper is terrible). The state-specific analysis was also able to offer target cover crop biomasses that offer significant weed control. Quantiatively-driven recommendations such as those are currently unavailable for the Corn Belt (CITE?).

Cover crops can suppress weeds by (i) competing for resources as live plants (e.g. sunlight, nutrients), (ii) altering the soil environment in ways that affect weed seed germination (e.g allelopathy, soil moisture retention), (iii) altering the environment in which weed seedlings develop as mulch (e.g. reducing temperatures, creating light stress). Each of these may have a suppressive or stimulatory effect on weeds, largely depending on context (CITE). Additionally, the production system in which cover crops are employed can have a large impact on the observed weed response. For example, many producers use cover crops as part of larger conservation plans that include zero-tillage (CITE). Cash crop diversification offers higher weed suppression in no-till systems (Weisberger et al. 2019), but the effect of the overall production system tillage regime on cover crop weed suppression is poorly understood in the Corn Belt (CITE contradicting studies). Furthermore, large questions remain about how cover crop interfaces with the cash crop can affect weed suppression in maize-soybean systems. Finally, cover crop weed research employs varying methodologies, and it is unclear how these can affect results and interpretation. To begin to address these research gaps we conducted a meta-analysis to understand the impact of (i) experimental design, (ii) environmental growing conditions, and (iii) managerial choices on cover crop weed control in maize-soybean systems in the US Midwestern Corn Belt.

**Methods**

Database search

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

available online). A literature was conducted in October 2018 using the following Boolean string: (weed\* AND ("cover crop\*" OR "green manure" OR "catch crop\*") AND ("corn" OR "maize" OR "soybean\*")). This resulted in a total of 676 studies that were screened for eligibility based on the following three criteria:

(i) Studies must have been conducted in a US ‘Corn Belt’ state, defined as a state in the contiguous Midwestern region with the largest acreages of maize acres harvested in the most recent five years of available data (USDA-NASS 2019) including: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin

(ii) Studies must have measured weed biomass and/or weed density

(iii) Studies must have included a treatment that tested the effects of a fall-planted cover crop followed by either maize or soybean against a treatment that included no cover crop holding all other factors constant.

Did we wind up accepting gray literature?

From this search, we screened the full text of 220 articles for inclusion in the database. From this, only 15 articles met our three criteria. *Can someone make a PRISMA diagram?*

Database development

We chose weed biomass and weed density as our response variables. 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 save for a treatment of a fall-planted cover crop and a no-cover control. Data were recorded for each site-year separately or averaged, depending on how they were reported. No zero values were reported. (this seems weird). For each comparison, a suite of accompanying information was extracted (Table X).

Statistical analysis

For both weed density and biomass, the response ratio was the value in the cover crop treatment divided by the no cover crop treatment (citation). The natural log of the response ratio was used for all statistical analyses, and values were back-transformed and presented as a percent change for interpretation purposes. To estimate over-all effect sizes, we fit a linear mixed-model using the lmer4 package (cite) in R (cite) to the log-transformed response ratio accounting for the random effect of study and non-parametric weighting based on sample sizes (cite). We used this weighting method because only 3 of the 15 studies reported variances.

Importance of modifiers was assessed using a generalized boosted regression tree (CITE). Significance of individual factors were assessed using a linear mixed model as described above, but with one fixed effect modifier included at a time. Significance was assigned at a p-value less than 0.05, but intermediate p-values <0.10 were investigated (CITE that Nature paper).

I’m meeting with a statistician to see if I can control for the effect of biomass while assessing the grass vs non-grass comparison, or if I can justify not doing that.

Need to do a sensitivity analysis to see if there is one study that is driving our results

**Results and Discussion**

Database overview

Fifteen articles (**Supplmentary material X**) fit our criteria, producing 123 response ratios for weed biomass and 119 response ratios for weed density, representing a range of site characteristics and managements representative of corn-soybean production systems of the Corn Belt (Fig 1; Table 1).

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| C:\Users\vnichols\Box Sync\1_Gina_Projects\proj_WeedMetaCC\_figs\manu_fig1_map-sites.png |
| Figure 1. Rough draft of Corn Belt map, with number of points and aridity index indicated (except for Missouri) |

**Table 1.** Management, experimental design, and site characteristics were extracted from each publication. The full database is available at XX.

|  |  |  |  |
| --- | --- | --- | --- |
| Category | Factor | Biomass (n = 123) | Density (n = 119) |
| ***Management*** | | | |
| System | Tillage | Tilled (n=30)  Zero-till (n=93) | Tilled (n=31)  Zero-till (n=88) |
|  | Time between cover crop termination and cash crop planting | -31 – 29 days | -31 – 13 days |
| Cover Crop | Type | Grass (n=46)  Non-grass (n=77) | Grass (n=31)  Non-grass (n=88) |
|  | Planting date | Aug 15 – Oct 18 | Aug 15 – Oct 31 |
|  | Planting density | 13.4 – 180 kg seed ha-1 | 9 – 135 kg seed ha-1 |
|  | Termination date | April 18 – June 18 | April 18 – June 18 |
|  | Termination method | Several methods (n = 3)  herbicides (n = 54)  mechanical (roller crimper, mowing; n = 29)  winterkill (n = 37) | Several methods (n = 3)  herbicides (n = 53)  mechanical (roller crimper, mowing; n = 22)  winterkill (n = 37)  none (n = 4) |
|  | Cover crop biomass at termination? | 130 – 9003 kg ha-1 | 0 – 9003 kg ha-1 |
| Cash Crop | Previous crop |  | Don’t see this |
|  | Subsequent crop | Maize (n=78)  Soybean (n=45) | Maize (n=73)  Soybean (n=42)  Data taken from both maize and soybean subsequent crops and averaged (n=4) |
|  | Cash crop planting date | April 20 – June 30 | April 27 – June 18 |
|  | Corn yield | 40-13500 kg ha-1 (yup, 40 is a real number coming from Hoffman, study 9) | 40-11200 kg ha-1 (yup, 40 is a real number coming from Hoffman, study 9) |
|  | Soybean yield | 300-3618 | 300-3310 kg ha-1 |
| ***Site*** | | | |
|  | State | Illinois (17)  Kansas (9)  Michigan (44)  Minnesota (12)  Nebraska (11)  Ohio (25)  Wisconsin (5) | Iowa (4)  Illinois (5)  Indiana (4)  Michigan (45)  Minnesota (16)  Missouri (18)  Nebraska (6)  Ohio (21) |
|  | Latitude | 38.0 - 45.7 | 38.7 - 45.7 |
|  | Longitude | 81.9 – 101W | 83.0 – 101W |
|  | Soil type | Loam (n = 46)  Sandy loam (n = 1)  Silt Loam (n = 67)  Silty Clay Loam (n = 9) | Loam (n = 59)  Silt Loam (n = 61)  Silty Clay Loam (n = 9) |
|  | Organic matter content | 1.5 - 4.15% | 1 – 3.4% |
|  | Aridity index\* | 0.37 – 0.94 | 0.44 – 0.96 |
|  | Publication year | 1993 - 2018 | 1993 - 2018 |
| **Experiment** | | | |
| Design | Number of replicates | 3 - 5 | 3 – 6 |
|  | Type of weed measured | Summer annual (86)  Winter annual (17)  Perennial (1)  Unknown (5) | Summer annual (75)  Winter annual (29)  Perennial (15) |
|  | Duration of experiment | <5 years (n=X)  >5 years (n=X) | <5 years (n=X)  >5 years (n=X) |
| Timing | Timing of weed measurement with respect to cover crop planting | Before (38)  After (119) | Before (38)  After (119) |
|  | Season of weed measurement | Spring (January-June; n = 19)  Summer (June-September; n = 104)  Winter(September – December; n = 4) | Spring (n = 36)  Summer (n = 79) |
| \*an integrated measure of temperature, precipitation and potential evapotranspiration were derived from location coordinates using the CGIAR-CSI Global-Aridity and Global-PET databases (Zomer et al. 2008). | | | |

NOTE: I don’t even think we should report the overall effects. There are significant moderators. Fernando and I have talked about this. We should be more nuanced.

For all categorical factors, we found weed biomass and density responded with the same patterns, but weed biomass responded more strongly (supplementary fig X). Three categorical modifiers had significantly different effects on weed biomass including cover crop type (grass, other), the timing of the weed measurement (before planting, after planting), and the type of weed measured (winter annual, summer annual, perennial; Fig X).

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Additionally, there was a significant relationship between cover crop biomass and weed suppression for both weed biomass (p=XX) and weed density (p=xx); Fig X).

Experimental Design Impacts Observed Response (needs more discussion probably)

Studies that measure weeds before cash crop planting may over-estimate the weed suppressive effects of cover crops. Weeds measured after crop emergence are likely of more interest to producers, as the will have survived the stresses of cover crop termination, crop planting, and pre-emergent herbicide application, and thus may represent true resource competition with the cash crop.

We found the cash crop following the cover crop (maize or soybean) had no effect on the measured response. This indicates the effects of the cover crop on weeds is not confounded by the differences in crop competition with weeds.

Environmental Context Is Not Significant

We found the context under which the trials were done (aridity index, soil type, soil OM) had no significant effect on the outcomes of the research. This indicates cover crop weed research done within the contiguous Corn Belt is valid for maize and soybean systems grown throughout, so open knowledge sharing via organizations like the Cover Crop Working Group (or whatever that is) and extension material developed within this area is valuable for the entire region. Discuss?

Management Tactics

Even after controlling for the effect of cover crop biomass, grass cover crops offered more weed suppression compared to non-grass. This could be due to several factors. The structural arrangement of grass plants could provide a larger amount of light interception per unit biomass compared to legumes (Storkey et al. 2015; CITE). Rye also exhibits an allopathic effect, which can inhibit seed germination (CITE) and reduce plant biomass (CITE, maybe Barnes and Putnam 1983). While brassica cover crops may also suppress weeds via allelopathy (Bjorkman et al. 2015), only 9 of the non-grass points were brassicas, and they did not exhibit significantly different suppressive effects compared to legumes (supplementary material X).

Note: rye grown in high fertility environments exhibits stronger allelopathy (Mwaja et al. 1995)

Interestingly, the method of cover crop termination and the tillage regime of the overall system had no effect on the weed suppression of the cover crop (supplemental table X). The largest managerial effects were manifested through the effect of cover crop biomass on weed suppression. We found ~4 Mg/ha of biomass are needed to reduce both weed density and biomass by 50%. This is similar to the amount needed in Pennsylvania grain-production systems, which require 2-6 Mg ha-1 to achieve significant weed suppression (Baribar et al. 2018). In assessments of monoculture and mixed cover crops done in Iowa (CITE Appelgate 2017), other places…, a winter rye monoculture (Secale cereal L.) produced the most biomass, but with averages still well under 1 Mg ha-1. Achieving 4 Mg ha-1 of cover crop biomass regularly under typical Corn Belt production scenarios and climates would be challenging. Farmer research in Iowa has shown termination a rye cover crop before maize is crucial to preventing yield drag, however allowing the cover crop to continue growing even after soybean planting has shown no significant effect on yields and has anecdotally improved weed control (cite PFI report). Fertilization cover crops is also another tactic that may improve Research supporting equipment, breeding, and agronomic innovations will be needed to optimize cover crop services such as weed control.

Yield considerations

Other studies have looked specifically at the effects of cover crops on subsequent cash crop yields (Miguez et al. 200x, Marcillo et al. 201x), however assessing whether there exists a trade-off between weed control and yield maintenance is a useful question. In our data, we found a no indication such a tradeoff exists (chi-square statistic = 1.78, p-value=0.18), with decreased yield being equally likely in scenarios with more or less weed pressure.

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| --- | --- | --- |
|  | Increased yields | Decreased yields |
| Decreased weeds | 41 | 25 |
| Increased weeds | 32 | 11 |

In fact, the majority of scenarios included a reduction in yield and an increase in weeds with the use of a cover crop (n = 73; XX%). Only 23% of the comparisons exhibited a ‘win-win’ situation, with a concomitant increase in cash crop yield and decrease in weed pressure. *We could use these categories as responses and do an analysis to see when/where these occur, but….I haven’t done that. Not sure it would produce anything useful….*

The non-significant effect of cover crops on maize and soybean yields has been corroborated through summaries of controlled field trials (Guillermo) and satellite data (Seifert et al. 2018).

Martinez-Feria et al. 2016 cite for modelling rye?

**Conclusions**

Weed biomass and density responded similarly to cover crops and their associated factors, with weed biomass responding more strongly. Reductions in weed density were likely less significant due to the short-term nature of the included studies (X-X years). Long term (+5 years) studies are needed to better understand if repeated reductions in weed biomass from cover crop use can reduce weed densities over time. Cover crop biomass production of at least 4 Mg ha-1 is needed to see a meaningful decrease in weed pressure. Independent of biomass production, grass species are the most effective at suppressing weeds. In conclusion, cover crops reduce weed biomass and may decrease weed density, but these reductions may be hard to achieve in Corn Belt production systems, and may not translate to an increase in yields.

Overall effects, I think we shouldn’t even include them.

Cover crops reduce weed biomass, but not weed density

*Overall, cover crops significantly reduced weed biomass (-57%, p = 0.02) but not weed density (+0.8%, p = 0.98; Fig X). This suggests cover crops are an effective in-season weed management tool. It is interesting to note that there were a number of experiments where cover crops led to an increase in weed density, counter to what we anticipated we might find. In general there are several possible explanations for why this occurred. It is possible that interactions with the cover crop biomass and herbicides applied for weed control and/or cover crop termination reduced product efficacy. It is also possible that for a variety of reasons the cover crop treatments created a more favorable environment for weeds (i.e. soil moisture retention). However, our results could simply be an artifact of the manner in which cover crops are studied in research. All of the included studies had been in place less than 5 years, and weed density reflects seedbank dynamics, which require longer to reach steady-state when exposed to changes in system managements (CITE). The strong effect on weed biomass suggests cover crops offer weed suppression mainly through competition of resoueces (e.g. light) – this information can help target management strategies to enhance weed suppression from cover crops.*

*The significant reduction of weed biomass without a concomitant reduction in weed density suggests cover crops promote smaller weeds compared to no-cover controls. This has important implications for the effectiveness of weed control measures. Smaller weeds are more susceptible to herbicides (CITE) and mechanical control (CITE), meaning cover crops are an important tool in an integrated weed management program.*

*Old Text from Andrea*

*Updated database does not show significant differences between termination methods groups for either weed biomass or weed density. Figures suggest that herbicides were the most effective termination method for reducing weed biomass, which could be different from the effect herbicides have on weed density but per seedling biomass would be less. Previously we had been describing this as: experiments that used herbicides or a combination of herbicides and mowing to terminate, or cover crops that were winter-killed were found to be more effective at weed control than cover crops terminated solely by crimping or mowing. In particular DeBruin found two glyphosate applications to be the most effective termination method. Evidence from studies in the southeast suggests that herbicides applied later in the season or with residual action were most effective at weed control in tandem with cover crops (Norsworthy et al. 2016; Wiggins et al. 2014; Montgomery et al. 2018).*

*Regression type figure of response ratios by biomass, could be sorted by crop following or cover crop species or both (F4)- note that if we include a regression line it not a good idea to include groups beyond the two panels*

*Cover crop species*

*Experiments included in our analysis utilized grass, legume and mixed cover crop species. We did not find differences in the efficacy of weed density control with different cover crop species, but did see a significant difference in cover crop species for weed biomass control (when analyzing type as a fixed effect in our mixed effects model, to be clear).*

*Figure of distributions broken out by cover crop species (F5 – if not included in F4). This mostly looks like the same trend as F2 will show –weed biomass is better controlled with cover crops than weed density. The stats results suggest that grass cover crop species are more effective at reducing weed biomass.*

*Crop following the cover crop – from here down still needs to be updated w/ new database info*

*Maybe no new figure here if included in F4*

*Crop yields*

*When experiments included yields we found that cover crops represented “win-win” scenarios 18% of the time, where weeds were reduced and yields were increased. “Lose-lose” situations (weeds increased and yield decreased) represented 46% of possible response ratios. Our analysis confirms other work that corn following a cover crop in the North Central region can decrease yields (Miguez and Bollero 2005; Marcillo and Miguez 2017). Note that these numbers need to be updated with the new database info.*

*Figure: Win-Win plot (F5 or F6)*

*Weather variables*

*Need to add more if this turns out to be something interest*

*Organic experiments*

*There were four organic experiments in the database and they were less effective at controlling weeds and improving yields; none of those response ratios fell into the win-win category.*

*Figure: Possible win win plot just for organic experiments, or distribution of these studies together*

Other potential discussion points:

Community of weeds vs individual weed species?

Is the method of planting stimulating weeds?

Possible long term weed seed bank changes with a cover crop

Management of herbicide resistant weeds

CC biomass relationship to yield