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RESEARCH

Global Meta-Analysis of Cotton Yield and Weed Suppression from Cover Crops

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ABSTRACT

Cover crops can reportedly improve soil fertility, suppress weed growth and pest pressure, and contribute to cotton (*Gossypium hirsutum* L.) yield improvements. To systematically evaluate cover crop effects on cotton yield and weed suppression, we conducted a random-effects meta-analysis investigating 10 moderating variables in 104 articles, yielding 1117 independent studies over 48 yr. Globally, cover crops increased cottonseed and lint yield by 6 and 5%, respectively, while decreasing weed biomass by 20%. Overall, leguminous cover crops increased seed cotton yield by 17 to 43% (*Vicia* spp. and *Pisum* spp., respectively). Monocots, nonlegume dicots, and legumes were effective at suppressing weed growth (21, 52, and 10%, respectively). Incorporation of cover crops by tillage (rather than chemical burn down) resulted in lint (14%) and seed (42%) yield increases. Cover crops increased cotton yields markedly on loamy soils, whereas there were lesser increases for other textures ($p > 0.05$). Greater efficacy of cover crops at controlling weeds was proportionate to soil silt content, which was inversely related to sand content. In addition, cover crops were effective at controlling multiple types of weed species; however, weed species with shorter maximum heights were most suppressed by cover crops. Overall, cover crops had a positive effect on cotton yield and weed suppression. Their effectiveness, however, can vary depending on soil texture, management strategy, and cover crop or weed genera. These results are useful in developing recommendations for suppressing weed growth and improving yield via cover crop integration in cotton cropping systems per geographic region and soil texture.

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Abbreviations: CI, confidence interval; ES, effect size; GMO, genetically modified organism.

Around the world, the use of legume and nonlegume cover crops has been a long-standing practice in crop production. In the United States, the use of cover crops has fluctuated over time; however, the popularity of this practice has increased substantially over the past 10 yr (USDA, 2018). Over 5 million ha of cover crops were planted on US farms in 2012 (USDA, 2012). As a provision of the 2014 Farm Bill (USDA, 2014), the NRCS provides financial incentives for farmers to plant cover crops as a means to address various states' soil and water quality and conservation issues. According to a 2017 national survey of 2102 producers conducted by the Conservation Technology Information Center, 88% reported growing cover crops (CTIC, 2017). Based on the survey, 86% of the respondents cited soil health as a primary reason for using cover crops, with yield consistency being listed second. In addition, cover crops are used to promote soil N (Tyler et al., 1987; Holderbaum et al., 1990; Tonitto et al., 2006), water quality (Snapp et al., 2005), soil organic matter (Thomazini et al., 2015), C sequestration (Poeplau and Don, 2015), plant productivity (Fageria et al., 2005), soil erosion control (Lu et al., 2000), suppression of pests (Kruger et al., 2013), and weed control (Nagabhushana et al., 2001; Wiggins et al., 2015). For these reasons, numerous studies evaluating cover crops have been conducted in cotton (*Gossypium hirsutum* L.) cropping systems,

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particularly on erodible land for effective erosion control in conservation tillage or no-till cotton systems, as cotton is a low-residue-producing crop (Tyler et al., 2000).

Meta-analysis is a statistical approach to combine multiple, independent studies (e.g., cover crops in cotton) across years, locations, soil texture, timeframes, and other experimental conditions to characterize consistency of outcomes (Fisher, 2015). The value of meta-analysis is that it allows the means of each primary study to act as replicates in much the same way that individual plants or plots serve as treatment replicates in primary studies. Weighted average relationships can be computed across studies to test for treatment effects, and the analysis can include covariates or factors that might help in understanding the effect. In meta-analysis, these covariates are termed explanatory variables, moderating variables, or simply, moderators. Averaging across studies has the limitation that experiments are often performed under nonstandardized, widely varying experimental conditions. However, this can also be an advantage, in that one can investigate whether a cover crop effect has been more pronounced or consistent under some experimental conditions compared with others. Consequently, we sought to answer the following questions in cotton cropping systems:

- Has cover cropping had a positive or adverse effect on cotton yield?
- Has cover cropping affected weed growth in this system?
- Does cover crop genus, weed genus, cover crop type, cotton cultivar, tillage practice, or soil texture affect the efficacy of cover crops on yield or weed growth?
- Have cover crop effects varied among geographic locations or across time, in particular, prior to year 2000 vs. after 2001 with genetically modified organism (GMO) trait technology adoption?

MATERIALS AND METHODS

Data Collection

On 19 June 2014, we conducted a two-tiered search (through that date) on the Web of Science Core Collection, CAB International, MEDLINE, Biological Abstracts, FSTA (Food Science and Technology Abstracts), and Zoological Record databases, using the ISI Web of Science search tool. We located 239,571 unique publications with the search terms: cotton OR *Gossypium*. A search of these records using the term "cover crop" resulted in 424 publications, composed of refereed articles, conference proceedings, research reports, and bulletins. With examination of these 424 eligible publications, 320 were excluded because they met our exclusion criteria: means for cover crop or no-cover crop treatments were not included, cotton yield or weed growth were not reported, article was a duplicate, article did not contain primary data (review or book), or they were not obtainable using interlibrary loan services (five articles). We did not include intercropping (cover crops grown simultaneously with cotton) studies, nor did we include studies that used weed count as the response variable. For the weed biomass effect size (ES), if an experiment included both weed and weed-free fallow no-cover-crop controls, we used the weed fallow no-cover-crop control in our analysis. If an experiment included herbicides applied over all treatments in season, we excluded the weed biomass ES but included the cotton biomass ES. We identified 104 articles that met our screening criteria (a full citation list and details of primary studies are provided in the supplemental material). Papers spanned 48 yr and were in English and Portuguese languages.

Treatment means and number of replications (sample sizes) were collected for each study. For publications reporting means for more than one no-cover-crop (control) treatment in a nonfactorial experiment, we used the no-cover-crop control that most closely approximated the cover crop treatment. If replications were given as a range, we used the smallest value. For studies that did not report number of replications, we used $n = 1$ unless LSD or SEs were provided, in which case we used $n = 2$. If data were provided in graphical form, means were extracted using WebPlotDigitizer (Rogatgi, 2011).

Multiple treatment combinations from one article were treated as independent studies (also referred to as trials or paired observations in the meta-analysis literature) and represented individual units in the meta-analysis. For example, Ashworth et al. (2018) and Li et al. (2013) examined the effects of two cover crop species over 3 yr, resulting in six studies from that article for lint yield ES. Vasilakoglou et al. (2011) studied control of three weed genera by four varieties of one cover crop species, resulting in 12 studies for the weed control ES. Although, the use of multiple studies from one publication has the disadvantage of increasing the dependence among studies that are assumed to be independent (Gurevitch and Hedges, 1999), the greater number of studies maximizes the meta-analysis' statistical power (Lajeuness and Forbes, 2003). This approach has been used often in agricultural and plant biology meta-analyses (Mayerhofer et al., 2013; McGrath and Lobell, 2013; Ferraretto and Shaver, 2015). Therefore, we derived 1117 studies from 104 articles. As in prior meta-analyses (Ashworth et al., 2018; Mayerhofer et al., 2013), we used the final time point in the meta-analysis for studies that included data for multiple time points in one season. One exception was weed control, as an article used in this meta-analysis reported means that were recorded at three time points during the season (Norsworthy et al., 2010). Considering that each year of an experiment provides varying growing conditions only weakly correlated with other years (repeated measures across years is not needed in our experience), we considered each year as an independent study in the meta-analysis.

Effect Size and Moderator Variables

We conducted meta-analyses for three response variables: seed cotton yield, lint yield, and weed biomass. Studies were evaluated via treatment ES, which was computed as the natural logarithm of the response ratio [ln(*R*)] of the cover crop to no-cover-crop means:

$$\mathrm{ES} = \ln(R) = \ln(Y_{\mathrm{CC}}/Y_{\mathrm{NCC}})$$

where Y_{CC} and Y_{NCC} are means of the responses for cover crop treatments and no-cover-crop controls, respectively (Rosenberg et al., 2000). This was used to calculate the overall effect (the summary or cumulative) of cover crop/no-cover-crop ES across studies (Borenstein et al., 2009). It is common to use a response ratio in meta-analyses of crop behaviors (Tremblay et al., 2012; Pelzer et al., 2014; Laurent et al., 2015), as it gives a standardized expression of treatment-induced changes and has direct biological and agronomic significance. The natural log transformation is needed to properly balance positive and negative treatment effects across response ratios (to maintain symmetry in the analysis; Borenstein et al., 2009). The ln(R) values and associated 95% confidence limits were then back-transformed to make the interpretation more intuitive. Values >1 indicate that a cover crop induced increase in the parameter of interest, whereas values <1 indicate that a cover crop induced decrease (e.g., weed mortality). When weed control was reported as a percentage, this was subtracted from 100 to give weed survival and a reasonable proxy for biomass. For the weed biomass ES, if an experiment included both weed and weed-free fallow no-cover-crop controls, we used the weed fallow no-cover-crop control in our analysis. If an experiment included herbicides applied over all treatments in season, we excluded the weed biomass ES but included the cotton biomass ES.

In addition to measures associated with crop growth and weed control, we recorded information from each study on several moderator variables that may modify cotton or weed response to a cover crop treatment (Tables 1–3). Each moderator had at least two categories (levels), and the data within each of these levels were collected from at least three studies from more than one article. These moderators were used as explanatory variables in the meta-analyses of summary effects. Specifically, we wanted to quantify whether some cover crop species were more effective than others at controlling weeds, how taxa (both cover crop and weed) influence cover crop efficacy, and how climatic conditions, cultural practices, or cotton cultivars may have affected cover cropping efficacy. Where moderator data were given for more than one time period, data associated with final seed cotton yield, lint yield, or weed biomass were used in the analyses. The chemical "level" included glyphosate, paraquat, oxyfluorfen, 2,4-dichlorophenoxyacetic acid (2,4-D), cyanazine, pendimethalin, and fluometuron. For cover crop fate, "tilled" included any study for which cover crop was disked or tilled in, without herbicides. For tillage system, conventional was defined as deep disking or plowing; conservation tillage included strip-till, para-till, and subsoiling; and no-till was planting into undisturbed cover crop or crop residue. Possible temporal changes in ES were evaluated using publication year as a moderator (Koricheva and Gurevitch, 2014), spanning 48 yr, over which data were published into eight equal 4-yr periods, and a ninth representing the years 1965 to 1981. For instance, Burzaco et al. (2014) suggests that quantitative reviews should take into account the positive effects of breeding progress on yield over time. We also compared studies that had been conducted prior to the year 2000 against those that had been conducted after 2001 (when GMO trait technologies such as herbicide tolerance and insect resistance [transgenic] became common in cotton cultivars).

Meta-Analysis

Our analyses followed the methodology and terminology of Borenstein et al. (2009) and were guided by the criteria suggested by Koricheva and Gurevitch (2014). We used a random-effects model for the meta-analyses, considering that true effects are likely to have varied across studies (rather than a fixed model, which assumes the same value or true effect for all studies). We estimated the summary effect (mean ES across studies) with Comprehensive Meta-Analysis (CMA) software (Version 3, Biostat; Borenstein et al., 2014). Individual studies within the meta-analyses were weighted using nonparametric variance:

$$V_{\ln(R)} = \frac{\left(n_{\text{CC}} + n_{\text{NCC}}\right)}{\left(n_{\text{CC}} \times n_{\text{NCC}}\right)}$$

where $V_{\ln(R)}$ is the variance of the natural log of the response ratio R, and n_{CC} and n_{NCC} are the samples sizes of the cover crop and no-cover-crop treatments (Rosenberg et al., 2000). Many publications did not report SEs or SDs, nor was sufficient information given in many instances to estimate these from LSD or

Table 1. Moderator analysis of cover crop influence on seed cotton yield.

Moderator	$Q_{between}$†	n‡	df§	I^2¶	p_{hetero}#
				%	
Cotton cultivar	7.2	366	4	0.0	0.126
Cover crop genus	21.9	539	11	0.0	0.026
Cover crop type	6.1	539	3	0.0	0.109
Cover crop fate	32.6	393	3	0.0	<0.001
Tillage type	3.2	454	2	0.0	0.204
Soil texture	51.7	495	4	0.0	<0.001
Location	52.2	540	7	0.0	<0.001
Harvest year	3.9	540	1	0.0	0.047
Publication year	43.8	540	8	0.0	<0.001

† $Q_{between}$, between-study variation (true heterogeneity).

‡ n, number of studies.

§ df, degrees of freedom, levels within a moderator.

¶ I^2 = the ratio of true variation (heterogeneity) to total variation.

p_{hetero}, p value that all observed (total) variation is due to sampling error (within-study variation). Seed cotton yield effect size (ES) is the cover crop/no-cover-crop response ratio. Analysis was conducted on log-transformed values [$ln(R)$] from each study. The levels of each moderator with their summary SE, confidence intervals, cover-crop-induced change as a percentage, number of studies, and significance values are given in Fig. 2–11.

other mean separation values. As has often been noted (Adams et al., 1997; Mayerhofer et al., 2013; Dalla Lana et al., 2015; Wang et al., 2015), it is not uncommon for measures of dispersion to have been omitted from publications, which makes weight calculating based solely on sample size (nonparametric variance) a necessity. Excluding studies that report sample size but not some measure of dispersion would represent a substantial loss of analytical power.

Heterogeneity was assessed with the Q statistic (a measure of weighted squared deviations) and quantified using I^2, a descriptive index that estimates the ratio of true variation (heterogeneity) to total variation across the observed range of ES (Higgins and Thompson, 2002; Huedo-Medina et al., 2006; Tremblay et al., 2012). I^2 is defined as

$$I^2 = (Q_{total} - df)/Q_{total}$$

where Q_{total} is total variation, degrees of freedom (df) represents within-study variation, and $Q_{total} - df$ is true heterogeneity, or between-study variation ($Q_{between}$). A value of 0% indicates no true heterogeneity, and positive values indicate true heterogeneity in the dataset, with larger values reflecting a larger proportion of the observed variation due to true heterogeneity among studies. Assumptions of homogeneity were considered invalid when p values for the Q test (p_{hetero}) for heterogeneity were <0.1 (Bristow et al., 2013; Iacovelli et al., 2014). We assumed a common among-study variance across moderator subgroups.

Publication bias is important to test, considering significant treatment differences are more likely to be published than nonsignificant findings. Potential publication bias was assessed statistically with Begg and Mazumbar rank (Kendall) correlation and represented graphically with funnel plots of ES values vs. their SEs (Begg and Mazumdar, 1994; Borenstein et al., 2009). In addition, sensitivity analyses were performed for the global summary effects by removing one study and rerunning the meta-analysis for every study. This shows how each study contributed to summary effects.

Table 2. Moderator analysis of cover crop influence on lint yield.

Moderator	$Q_{between}$†	n‡	df§	I^2¶	p_{hetero}#
				%	
Cotton cultivar	15.0	283	5	0.0	0.010
Cover crop genus	12.1	441	8	0.0	0.147
Cover crop type	0.2	437	2	0.0	0.927
Cover crop fate	3.4	398	2	0.0	0.187
Tillage type	0.4	309	2	0.0	0.810
Soil texture	13.9	426	6	0.0	0.031
Location	17.4	441	9	0.0	0.043
Harvest year	0.1	441	1	0.0	0.831
Publication year	3.2	441	8	0.0	0.919

† $Q_{between}$, between-study variation (true heterogeneity).

‡ n, number of studies.

§ df, degrees of freedom, levels within a moderator.

¶ I^2 = the ratio of true variation (heterogeneity) to total variation.

$p_{hetero,}$ p value that all observed (total) variation is due to sampling error (within-study variation). Seed cotton yield effect size (ES) is the cover crop/no-cover-crop response ratio. Analysis was conducted on log-transformed values [ln(R)] from each study. The levels of each moderator with their summary ES, confidence intervals, cover-crop-induced change as a percentage, number of studies, and significance values are given in Fig. 2–11.

Table 3. Moderator analysis of cover crop influence on weed biomass.

Moderator	$Q_{between}$†	n‡	df§	I^2¶	p_{hetero}#
				%	
Cotton cultivar	30.9	174	3	12.7	<0.001
Cover crop genus	16.6	174	6	7.0	<0.001
Cover crop type	29.6	170	2	11.0	0.011
Cover crop fate	1.1	174	1	0.0	<0.001
Tillage type	0.0	171	1	0.0	0.287
Soil texture	32.2	174	4	12.7	0.905
Location	25.2	174	3	11.6	<0.001
Harvest year	10.4	174	1	6.8	<0.001
Publication year	12.8	174	3	7.0	0.001
Weed genus spp.	28.9	163	5	13.3	0.005

† $Q_{between}$, between-study variation (true heterogeneity).

‡ n, number of studies.

§ df, degrees of freedom, levels within a moderator.

¶ I^2 = the ratio of true variation (heterogeneity) to total variation.

$p_{hetero,}$ p value that all observed (total) variation is due to sampling error (within-study variation). Seed cotton yield effect size (ES) is the cover crop/no-cover-crop response ratio. Analysis was conducted on log-transformed values [ln(R)] from each study. The levels of each moderator with their summary effect sizes, confidence intervals, cover-crop-induced change as a percentage, number of studies, and significance values are given in Fig. 2–11.

RESULTS AND DISCUSSION

Analyses were conducted on natural logs and back-transformed to raw ratios. Summary of ES values—cover crop/no-cover-crop response ratios—are depicted in the forest plots (Fig. 1–11). The average percentage changes caused by cover crop treatments are shown to the left of the forest plots, as are numbers of studies in each summary effect and probabilities that the summary effects are zero at $p < 0.05$. Statistical significance of summary effects is also denoted by confidence intervals (CIs). If CIs do not cross the 1.0 vertical dotted line, they are different from no-cover-crop treatments at $p \leq 0.05$. It should be noted that in meta-analysis, unlike with primary studies, the magnitude of the summary effect is often regarded as of equal or greater importance than whether it statistically differs from zero (Cooper, 2016). Lack of statistical significance in meta-analysis is often due to insufficient numbers of studies and/or small sample sizes (Cumming, 2012)

The summary effect for overall seed cotton yield was 1.06 (p = 0.01, CI = 1.014–1.114), indicating that cover crops increased seed cotton yield by an average of 6% over all 540 studies (Fig. 1). The ES values for individual studies were <0.95 for 110 (20%) studies, between 0.95 and 1.05 for 127 (24%) studies (negligible cover crop effect) and

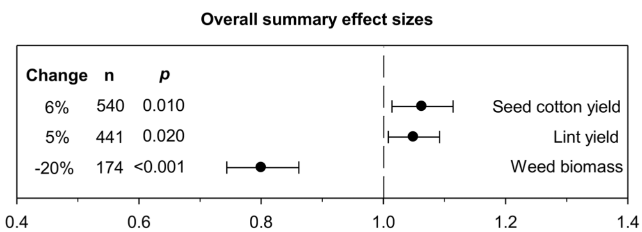

Fig. 1. Weighted, overall summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass. Change refers to raw percentage increase in the ES induced by cover cropping. n is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

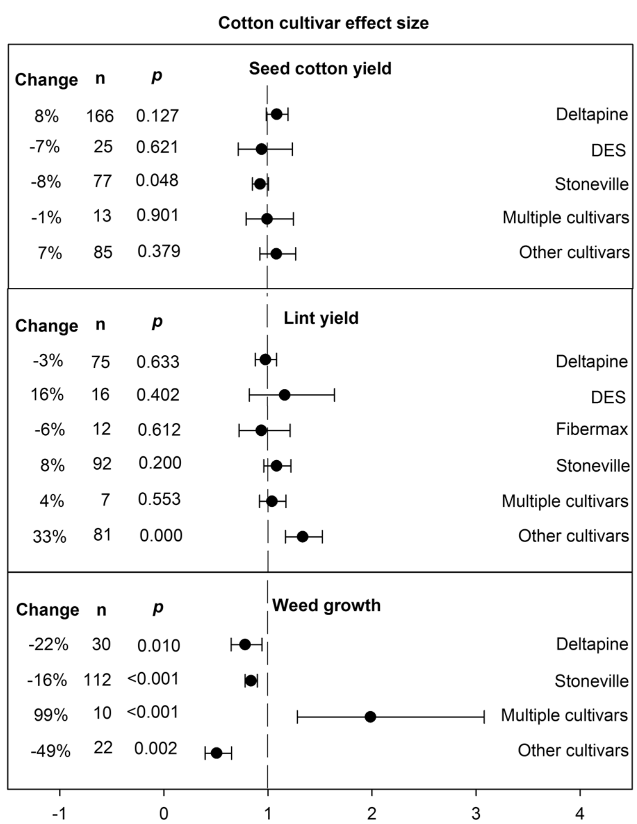

Fig. 2. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to cotton cultivar. Abbreviation "DES" refers to the Delta Experiment Station, Stoneville, MS. Change refers to raw percentage increase in the ES induced by cover cropping. n is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

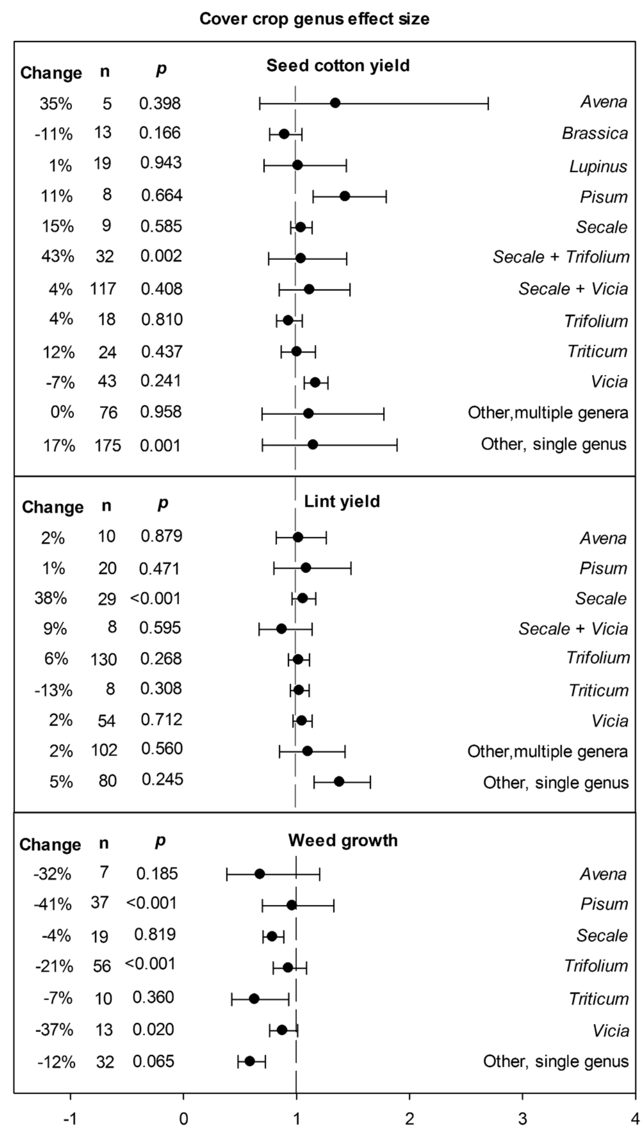

Fig. 3. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to cover crop genus. Change refers to raw percentage increase in the ES induced by cover cropping. n is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

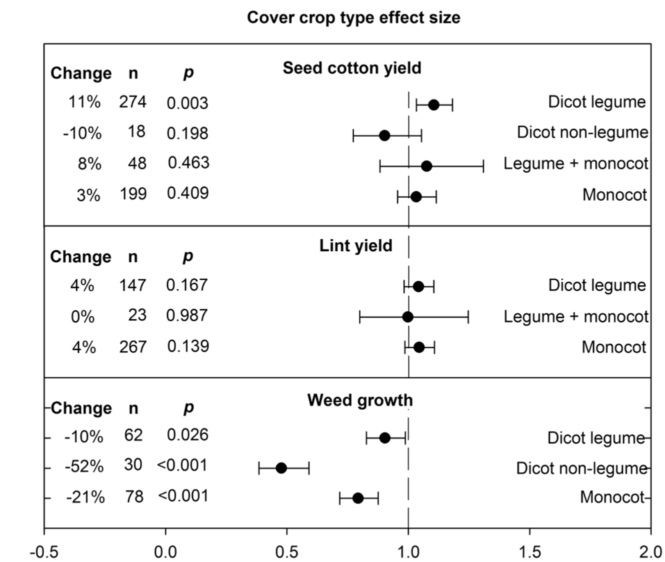

Fig. 4. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to cover crop type. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. *p* ≤ 0.05 indicates that the summary effect was different than zero

>1.05 for 303 (56%) studies. The overall summary effect for lint yield was close to that of seed cotton yield, at 1.05 (p = 0.02, CI = 1.01–1.09). Thus, cover crops increased lint yield by an average of 5% over the 441 studies. Effect sizes for individual studies were <0.95 for 99 (22%) studies, between 0.95 and 1.05 for 139 (32%) studies (negligible cover crop effect) and >1.05 for 203 (46%) studies. A 6% increase in seed cotton yield and a 5% increase in lint yield may seem negligible; however, these increases are of substantial economic benefit to growers, despite cover crop establishment costs. For example, the USDA's cover crop economics tool estimates an additional US$33 net profit per 0.4 ha for a 5% cover crop yield increase (USDA, 2015). Cover crops have been shown to result in better yields for other crops as well (Kumar et al., 2005; Wang et al., 2008), although these effects are often variable in other cash crops (Kaspar and Bakker, 2015).

The overall weed biomass summary effect was 0.80 (p < 0.0001, CI = 0.744–0.862); weed biomass decreased 20% on average from cover cropping (n = 174 studies; note: weed biomass is a notoriously variable parameter and should be factored into results). Effect sizes for individual studies were <0.95 for 101 (58%) studies, between 0.95 and 1.05 for 43 (25%) studies (negligible cover crop effect), and >1.05 for 30 (17%) studies. The 20% decrease in weed biomass due to cover crop use has substantial implications. Weeds reduce overall yields in many crops, including cotton (Wood et al., 2002; Barnett and Steckel, 2013; Ma et al., 2015). Since the release of glyphosate-resistant cotton cultivars in 1997 (Monsanto, 2016), weed species have increasingly become resistant to glyphosate

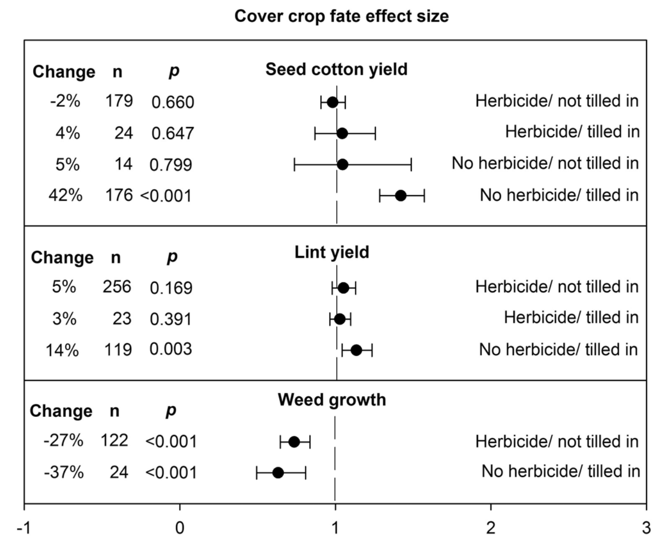

Fig. 5. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to cover crop fate. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. *p* ≤ 0.05 indicates that the summary effect was different than zero.

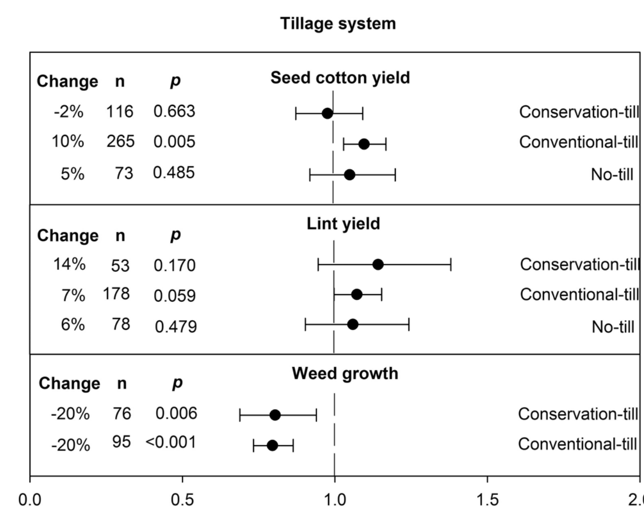

Fig. 6. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to tillage system. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. *p* ≤ 0.05 indicates that the summary effect was different than zero.

(Steckel, 2007; Steckel and Gwathmey, 2009). The results of this meta-analysis indicate that incorporating cover crops into a farm management plan may help to eliminate the adverse effects of glyphosate-resistant weed species.

Moderator Impacts on Lint and Seed Yield and Weed Biomass Production

We examined several moderating variables to determine if they were associated with the size of the cover crop effect on yield or weed biomass. Heterogeneity statistics are shown in Tables 1, 2, and 3 for seed cotton yield,

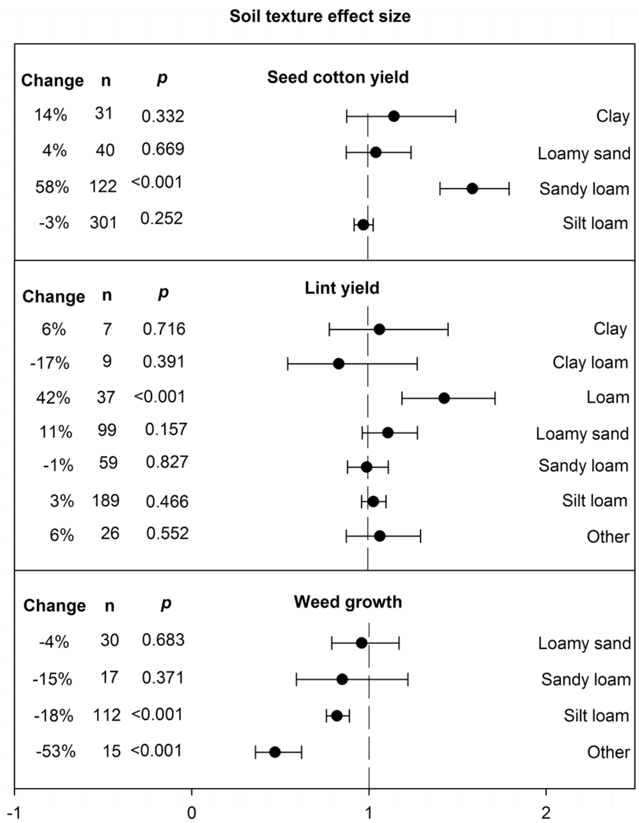

Fig. 7. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to soil texture. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

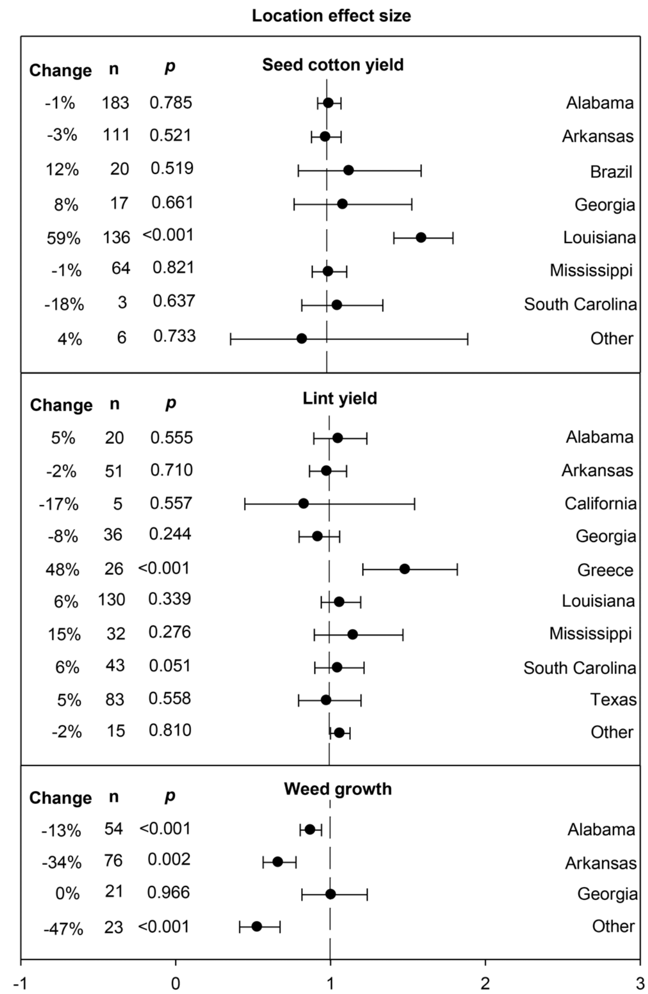

Fig. 8. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to experimental location. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

lint yield, and weed biomass, respectively. There were sufficient studies involving Deltapine, Delta Experiment Station, Fibermax, and Stoneville cultivars to compare these individually. Per our criteria, cotton cultivar groups represented by fewer than three studies or by just one article were combined into an "other" category for this moderator (15 cultivars comprised "other"). "Multiple cultivars" refers to a study in which more than one cover crop cultivar was grown in the same plot.

Cotton cultivar did not affect cover-crop-induced changes in seed cotton yield (Fig. 2). The change was only significant for cultivar Stoneville (cover-crop-induced decrease of 8%). The size of the cover crop effect on lint yield varied more among cultivars than it did for seed cotton yield, from −6% for Fibermax to 33% for the "other" category (Fig. 2). None of the individual cultivars had lint yields that were affected by cover cropping. For weed biomass, which in general was more affected by cover crops than cotton yield, cultivars differed. For the relatively few studies that contained multiple cotton cultivars, represented chiefly by one article (Webster et al., 2013), weeds flourished, with twice the weed biomass in cover crop treatments than in treatments without cover crops (Fig. 2). This indicates the need for cotton cultivar consistency when conducting cover crop research. Cover cropping reduced weed biomass by an average of 16% in cultivar Stoneville and 22% in Deltapine. Cultivars representing the 49% decrease in weed biomass were Fibermax, Campo, and Sicot (Duggan et al., 2005; Moran and Greenberg, 2008; Vasilakoglou et al., 2011).

Among the 12 levels in the cover crop genus moderator, two showed significant effects on seed cotton yield: a 43% increase with *Pisum* (32 of 181 studies) and a 17% increase with *Vicia* (175 of 381 studies; Fig. 3). Brassicaceae spp., *Trifolium* spp., *Triticum* spp., lupine (*Lupinus albus* L.), and rye (*Secale cereale* L.) (alone or combined with other cover crops) had smaller and insignificant summary effects (between −11 and 15%). *Pisum* and *Vicia* are both leguminous species. These legumes may fix anywhere from 35 to 67 kg N ha^{-1} (Ashworth et al., 2015a, 2015b; Flynn and Idowu, 2015). Consequently, increased seed cotton yield under these genera is likely due to additional N produced by legumes. The "other" category, composed of *Hordeum*

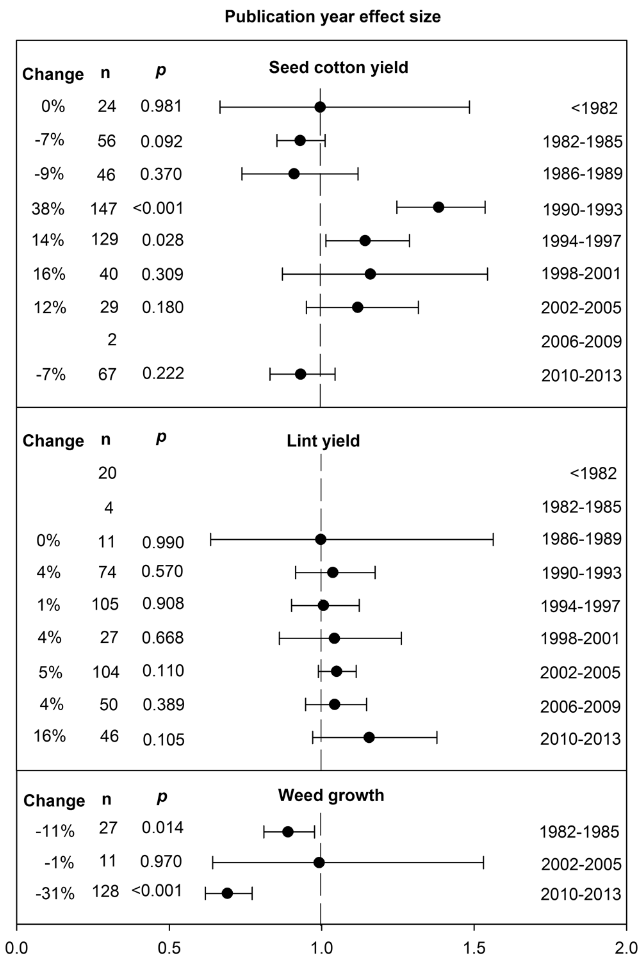

Fig. 9. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass over time. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

spp., *Origanum* spp., *Pennisetum* spp., *Sorghum* spp., and *Triticosecale* spp., was the sole category of the cover crop genus moderator to have an impact on lint yield, increasing it by an average of 38% (29 of 441 studies, Fig. 3). Given the number of genera included in this category, it is difficult to speculate the cause of increased lint yield (but note the absence of legumes). One of the purposes of meta-analysis is to identify directions for future research; the 38% increase in lint yield for this moderator indicates a need for more research with these five genera.

A cover-crop-induced decrease in weed biomass was seen with each individual cover crop genus in the analysis, although the decrease was significant only for *Secale*, *Triticum*, and the "other" category (composed predominantly of *Brassica* and *Origanum*) (Fig. 3). *Triticum* (−37%) has resulted in substantially less weed biomass than *Secale* (−21%). The C/N ratio for *Secale* and *Triticum* is nearly five times than that of legumes (USDA, 2011). Since N is the primary limiting factor for microbial decomposition of plant biomass (Hobbie et al., 2012; Talbot and Treseder,

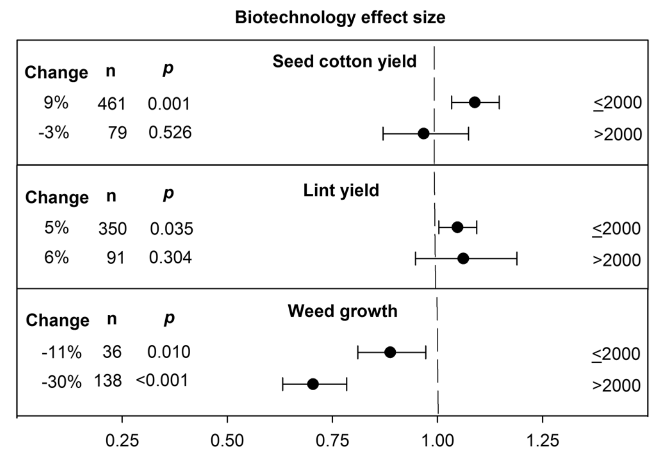

Fig. 10. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on seed cotton yield, lint yield, and weed biomass in relation to introduction of transgenic cultivars. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

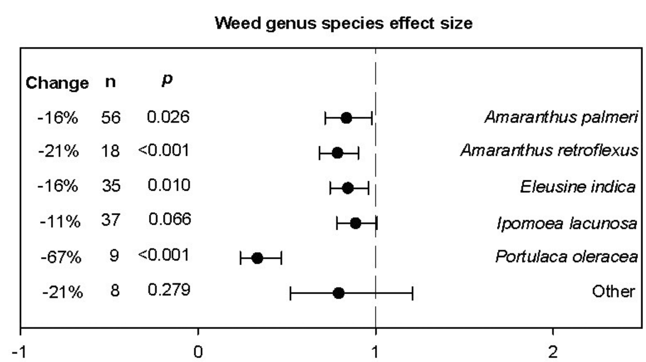

Fig. 11. Weighted summary effect sizes (ES, response ratios) and 95% confidence intervals for cover crop influence on weed biomass in relation to weed identity. Change refers to raw percentage increase in the ES induced by cover cropping. *n* is number of studies contributing to the ES. $p \leq 0.05$ indicates that the summary effect was different than zero.

2012), it is speculated that these cover crop genera decomposed at a slower rate than leguminous genera, providing a longer period of mulch for weed suppression.

Monocotyledonous and nonlegume dicotyledonous cover crops differed little in their impact on seed cotton or lint yield (Fig. 4). Reflective of the cover crop genus moderator, legume dicots increased seed cotton yield by 11%, likely due to additional soil N (Flynn and Idowu, 2015). Both monocot and dicot cover crops have been associated with decreased weed growth. Nonlegume dicots resulted in about five times as much weed suppression as legumes (10 vs. 52%, Fig. 4). Separating weed suppression results into dicot–legume and dicot–nonlegume supports the hypothesis that poorer weed suppression by legumes than by other cover crop types is due to the added N accelerating decomposition of plant tissue by soil microbes.

Tilling in a cover crop without initially killing it with herbicides resulted in increased seed cotton yield by 42% (Fig. 5). Use of herbicides and not mechanically tilling in the cover crop had negligible effects on seed cotton yield. These findings were similar for lint yield, although the influence of tilling alone was considerably smaller (14%). Cover crop suppression of weed growth, as mediated by cover crop fate, ranged from 27 to 37%. This meta-analysis indicates that the best results may be obtained by tilling in a cover crop without first killing it with an herbicide. Disease can cause significant declines in cotton yields (Farooq et al., 2011; Karademir et al., 2012). There are many reports indicating that tillage is associated with suppression of several disease-causing organisms (Bailey and Lazarovits, 2003; Janvier et al., 2007). Reasons that tillage is suppressive to disease include a faster decomposition of residues and exudates from some cover crops, which are known to have biocidal properties for microorganisms (Charron and Sams, 1999; Handiseni et al., 2013). We speculate that higher seed cotton and lint yields in tilled systems are at least in part tied to reduced disease pressure.

Seed cotton yield increased 10% due to cover cropping in conventional tillage systems ($p > 0.05$, Fig. 6). Cover cropping in conservation tillage and no-tillage systems had little effect on seed cotton yield. Cover cropping has been associated with modest increases in lint yield, from 6 to 14%. Cover cropping resulted in an average of 20% reduction in weed biomass in both conservation and conventional tillage systems. Unlike conventional tillage, conservation and no-till systems leave part or all of the cover crop residue on the soil. The complete incorporation of cover crop residue that takes place in conventional tillage systems allows for faster decomposition of residues on which some disease organisms can survive saprophytically (Janvier et al., 2007). As noted above, this can lead to reduced disease pressure, which may be why seed cotton yield is higher in conventional tillage systems.

Cover crop effects on seed cotton yield varied with soil texture (Fig. 7). Seed cotton yield on sandy loam soils increased on average of 58% from cover cropping but not lint yield (−1%). There was essentially no effect of cover crops on silt loam or loamy sand. The cover-crop-induced increase of 14% in clay soils was not significant. The greatest and only significant influence of cover cropping on lint yield has been associated with loam soils (42% increase, Fig. 7). Loamy soils typically possess more nutrients and retain moisture well but also have better drainage than some other soil textures (USDA, 2016). These characteristics may explain why there was such a marked increase in lint yield in loam soils compared with other soil textures.

The greatest influence of cover cropping on weed growth occurred in the "other" category (loam, silty clay loam, and clay), resulting in a 53% decrease in weed biomass. Also, weed biomass decreased due to cover cropping in silt loams by 18%. The ability of cover crops to reduce weed pressure improved as soil sand content decreased, while the silt content increased as illustrated by the USDA's soil texture pyramid (USDA, 2016). Weed seeds have a greater tendency to reside near the soil surface in siltier soils, regardless of tillage type, whereas they can be relocated to lower soil depths in sandy soils under certain tillage regimes (Menalled, 2008). The greater weed control observed in siltier soils may therefore be due to more weed seeds present at shallow depths, resulting in higher weed populations in fallow controls.

Geographic location had a substantial influence on the extent that cover cropping affected seed cotton yield (Fig. 8, $p_{\text{hetero}} \leq 0.001$). Cover cropping increased seed cotton yield by an average of 59% across the 136 studies representing Louisiana (Fig. 8). However, 86 of the studies taking place in Louisiana came from one publication. As described below, a sensitivity analysis removing those studies lowered the summary effect from 86 to 0.3% and the significance value of that ES to nonsignificant. It is important to note that the one Louisiana publication contained rare continuous data collected over decades (Millhollon and Melville, 1991). This indicates that the cumulative benefits of cover cropping may be best observed after many years of the practice. Cover cropping in other locations was associated with much smaller, insignificant increases or lack of effect. Lint yields were most affected by cover cropping (48% increase) in two Greek experiments (Vasilakoglou et al., 2006, 2011) conducted on loamy soils (Fig. 8). Loamy soils are associated with higher lint yields (Fig. 7), which may explain the higher yield in this location. Lint yield summary effects for other locations ranged from −17 to 15%, indicating strong location effects on the efficacy of cover crops to suppress weed growth in cotton systems. Weed biomass was reduced by cover crops by an average of 34% in Arkansas, 13% in Alabama, and 47% in "other" locations (Greece, Australia, Texas, and Mississippi). Cover crops had no effect on weed biomass in experiments conducted in Georgia.

Temporal Effects of Cover Cropping in Cotton Systems

Koricheva and Gurevitch (2014) recommended testing whether a summary effect has changed over time when studies comprising the effect have been published over many years. Changes in the summary effect could potentially result from publication bias, changes in methodology, or real biological changes. Investigating chronology (year of publication), as a moderator (consisting of seven 4-yr periods, with an eighth representing work published before 1982), revealed that cover crop influences on seed cotton yield peaked in the early 1990s at 38% and were over twice as influential then than in any other time period (Fig. 9). From the mid-1990s through 2005, the cover-crop-induced seed cotton yield increase was fairly steady at 12 to 16%. Prior to 1989, cover cropping had little effect on yield, and the same was true in recent years (2010–2013). Lint yield showed a different response than seed cotton yield to cover cropping over time, with the most recent period (2010–2013) averaging 16% increases and prior periods showing little to no effect. Therefore, historically, cover crop influence on seed cotton yield peaked in the early 1990s, with recent studies (published after 2000) suggesting fewer benefits from cover cropping in cotton systems likely due to the emergence of transgenic, herbicide-tolerant cultivars.

For weed biomass, only three 4-yr periods had sufficient studies to be included in the analysis. Weed control was more responsive to cover cropping in recent years, with weed biomass decreasing 31% during 2010 to 2013 (Fig. 9). The rise in glyphosate-resistant weeds has made it necessary to find alternate methods of weed control (Steckel et al., 2006, 2008; Korres and Norsworthy, 2015); hence, there is an increased interest in research involving cover crops for weed control.

In addition to examining the temporal effects, we compared studies published in 2000 and earlier with those published after 2001, as an indirect way to compare the influence of cover cropping in transgenic and nontransgenic cotton. Cover crops resulted in a 9% increase in seed cotton yield in nontransgenic cultivars (prior to 2001, $n = 461$), but no effect on seed cotton yield was observed for transgenic cultivars (Fig. 10). Weed biomass, however, was substantially less with cover crops post-2000 than before 2001 (−30 vs. −11%, respectively).

Weed Genus Impacts on Cotton Yield and Weed Biomass Effects

A 10th moderator, weed genus, was included in the analysis of the weed biomass ES. Five weed taxa were represented by sufficient numbers of studies to be analyzed individually, with the remaining, less studied taxa grouped as a sixth level of this moderator (Fig. 11). The "other" category contained data for *Echinochloa crus-galli* (L.) P. Beauv. (barnyardgrass), *Setaria verticillata* (L.) Beauv. (bristly foxtail), and *Urochloa ramosa* (L.) Nguyen (browntop millet) (Vasilakoglou et al., 2011; Molin and Stetina, 2013). Use of a cover crop reduced weed growth 67% for *Portulaca oleracea* L., whereas control of other taxa was less effective. Biomass of important weeds species in cotton—*Amaranthus palmeri* S. Watson (Palmer amaranth), *A. retroflexus* L. (redroot pigweed), *Eleusine indica* (L.) Gaertn. (goosegrass), and *Ipomoea lacunosa* L. (pitted morningglory)—was reduced by 11 to 21% with cover cropping. *Portulaca oleracea* (common purslane), or purslane, is a shorter plant than the other species examined. It reaches a maximum height of 40 cm, whereas *Amaranthus* species can reach heights of 1.8 to 2.4 m (Alam et al., 2014; Schonbeck, 2014). Cover crops would better compete for light against purslane, thus more effectively suppressing it.

Six of eight moderators had significant heterogeneity for seed cotton yield, and seven of nine moderators had significant heterogeneity for weed biomass. Only three of eight moderators had significant heterogeneity for lint yield. It is important to note that although a significant p_{hetero} value denotes that true effects vary, the converse is not true. A nonsignificant p_{hetero} value should not be considered evidence that there are no real differences, as there may have been insufficient power to detect differences (Borenstein et al., 2009). Weed biomass showed more heterogeneity than yield, in terms of positive I^2 values. I^2, a measure of the amount of between-study or true variance as a percentage of total variance, equates to zero when df exceeds Q_{total} (i.e., when all variance is statistically defined as within-study variance). Where $I^2 = 0$, within-study variation was large. In meta-analyses having many studies and large within-study variation, which is often the case in plant biology, I^2 often equates to zero, even when p_{hetero} values are <0.1 and signify significant heterogeneity.

Potential Data Analysis Bias

We did not see evidence of publication bias. Visually, the funnel plots for each of the summary effects showed no pattern that would reflect bias toward not reporting small or negative ES. Large or small studies across the range of SEs had the expected variability around the common ES. Within the Begg and Mazumbar rank correlation test, each of the summary effects had absolute Kendall value <0.14, indicating no publication bias (no tendency for ES to increase as study size decreases).

The stability of the overall summary effects was assessed with sensitivity analysis. The sensitivity analysis showed a close continuum of one-study-removed values for lint yield and weed biomass, with the largest jump in ln(R) no more than 0.001 (raw percentage change of 0.1%) for the removal of any one study. With the exception of four studies (individual study details in the supplemental material), the same was true of seed cotton yield. The study with the largest influence on seed cotton yield was study 998 (Brown and Whitwell, 1985). Its ES was 0.43 [ln[R] = −0.847], and its removal from the analysis changed the raw value of the summary effect by 1.3% (from a cover-crop-induced influence of 6.3 to 7.6%). Assessing the sensitivity of summary effects to individual articles may also be important in interpreting meta-analyses, especially for articles with large numbers of studies. Removing the 86 studies of Millhollon and Melville (1991) changed the summary effect for seed cotton yield from 1.00 to 1.86 and removes the statistical significance of the impact of cover crops. Meta-analysis of the 86 studies alone gives a summary effect of 1.83; cover cropping was associated with an overall 83% increase in seed cotton yield over the 30 yr of those 86 Louisiana studies. The articles having the next largest number of studies each had summary effects very close to the overall summary effect of 6%, 7.0% for the 42 studies of Keisling et al. (1994), and 6.8% for the 42 studies of Scott et al. (1990). The publication with the largest number of studies with lint yield data was Boquet et al. (1997a). Removing these 36 studies changes the summary effect for lint yield from 1.04 to 1.05 (i.e., a negligible change in cover crop effect from a 4.9% increase to a 5.2% increase). Also removing the second article published by this group in 1997 and its 20 studies (Boquet et al., 1997b) had a negligible impact on the overall summary effect, changing the average cover crop-induced increase from 4.9 (441 studies) to 5.1% (385 studies). The article with the most studies for weed biomass was Norsworthy et al. (2011); removing these 38 studies changed the overall summary effect of cover cropping from −20 to −15%. The article with the next most studies for weed biomass was Norsworthy et al. (2010); removing these 36 studies changed the overall summary effect of cover cropping from −20 to −23%. The summary effect for each of the two articles alone was −49% for 2011 and −9% for the 2010 article. The value of cover-crop-induced weed control without the 74 studies from this one group was −17%, very close to the overall effect of −20%. We hold the view that the most robust meta-analysis includes the most data, and we did not discount a report for providing a relatively large amount of reliable data. We do note the importance of evaluating the impact of particular studies and articles, as the reasons for these impacts (if they can be identified) can suggest potentially productive additional research areas.

CONCLUSIONS

Analysis of studies in this meta-analysis revealed that cover crop impacts on seed cotton yield, lint yield, and weed suppression varied substantially by geographic location, soil texture, tillage type, cover crop genera, and method of cover crop termination. These results may be useful for developing future research and recommendation strategies within geographic regions, soil texture for which cover crops might be best suited, and choices of cover crops that have high probability of increasing yields and/or suppressing weeds.

Conflict of Interest

The authors declare that there is no conflict of interest.

Supplemental Material Available

References of data used in the meta-analysis investigating 10 moderating variables in 104 articles, yielding 1117 independent studies over 48 yr, are available in a supplemental file.

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