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REVIEW & INTERPRETATION

Impact of Cover Crop Management on Level of Weed Suppression: A Meta-Analysis

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ABSTRACT

We conducted a previous systematic and meta-analysis review that showed differences in results from studies that evaluated the effectiveness of cover crops for weed suppression in cropping systems; these differences were largely due to management approaches used in growing the cover crop and main crop. The current meta-analysis provides a quantitative review on how cover crop and main crop management practices influence the impact of cover crops on weed suppression. The meta-analysis used observations from 53 studies published from 1990 to 2018. Cover crop biomass was inversely related to the amount of weed biomass (r^2 = 0.67) and weed density (r^2 = 0.64). In general, the meta-analysis shows that cover crops provided a range of weed suppression depending on management decisions such as choice of cover crop species, cover crop sowing season (fall or spring), sowing dates within seasons, seeding rate, termination date, delay in main crop planting date after cover crop termination, tillage system under which the cover crop was produced, and integrating the cover crop with other weed control inputs. For example, grass cover crop species provided greater weed suppression than broadleaf species. Fall-sown cover crops provided greater weed suppression (weighted mean of response ratio [R^*] = 0.19) than spring-sown cover crops (R^* = 0.48) by the summer. Weed suppression increased by increasing seeding rate of cover crops from 1× (R^* = 0.50) to 2× (R^* = 0.27) or 3× (R^* = 0.10). In addition, cover crops provided greater weed suppression in reduced tillage systems (R^* = 0.19) than no tillage (R^* = 0.29). The differential weed suppression provided by these management approaches suggests that a cover crop management approach should be rightly selected for weed suppression benefits.

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Abbreviations: CI, confidence interval.

Weed suppression is one of several benefits that could be achieved by including a cover crop in a cropping system. Globally, the adoption of cover crops is gaining more attention, especially in reduced and no-tillage systems, partly due to increasing interest in reducing the development of herbicide-resistant weeds, and enhancing the sustainability of agroecosystems (Teasdale, 1993; Dorn et al., 2015; SARE/CTIC, 2017). A recent survey showed that land area planted with cover crops in the United States has nearly doubled over the last 5 yr as farmers have reported increased crop yields and improved suppression of weeds (SARE/CTIC, 2017). Cover crops could provide weed suppression physically through smothering (Hutchinson and McGiffen, 2000); ecologically through competition for limited resources such as nutrients, water, and light (Teasdale, 1996; Hartwig and Ammon, 2002; Mirsky et al., 2013; Adigun et al., 2014; Osipitan and Dille, 2017); or chemically through release of allelochemicals from living and dead biomass (Barnes et al., 1987; Weston, 1996; Caamal-Maldonado et al., 2001; Kunz et al., 2016).

Weed suppression using cover crops in conservation tillage systems was comparable with chemical and mechanical weed control in many situations, particularly at early stages of crop growth according to a recent meta-analysis study (Osipitan et al., 2018). The level and duration of weed suppression provided by

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a cover crop depends on its inherent characteristics such as persistence of their residue, phytoallelopathy, biomass productivity, surface cover, and agronomic management strategies adopted (Mafakheri et al., 2010; Mirsky et al., 2011; Campiglia et al., 2014). Some of the key agronomic management strategies that could influence the effectiveness of cover crops for weed suppression include choice of cover crop species, planting date, seeding rate, fertilization practices, termination method and timing, tillage system, time between cover crop termination and main crop planting, type of main crop, and crop cultural practices.

Previous studies have shown that the level of weed suppression depends on the type of cover crop species used (Akemo et al., 2000; Hayden et al., 2012; Baraibar et al., 2018). For example, during the growing season, a cereal rye (*Secale cereale* L.) cover crop provided greater weed suppression (75–85%) than a pea (*Pisum sativum* L.) cover crop (0–56% weed suppression) (Akemo et al., 2000). Increasing seeding rate of the cover crop species could increase the biomass production and soil surface cover needed for greater weed suppression (Brennan and Smith, 2005; Ryan et al., 2011). For example, increasing the seeding rate of a cover crop by three times of the standard rate reduced weed biomass from 300 to <100 kg ha^{-1} (Brennan et al., 2009).

Planting date for a cover crop usually depends on the species characteristics, discretion of growers, and weather conditions (Fayaud et al., 2014). Research has shown that planting cover crops in fall or spring influenced production of cover crop biomass and thus affected subsequent weed suppression; mostly, the earlier planting date resulted in greater weed suppression (Saini et al., 2006; Anugroho et al., 2009; Wells et al., 2016; Sturm et al., 2017). The termination date is as important as the planting date. A study showed that a delay of 4 wk in termination of crimson clover (*Trifolium incarnatum* L.), a fall-sown cover crop, resulted in 10 times more biomass production with subsequent greater weed suppression (Saini et al., 2006).

A previous review suggested that there were differences in studies that evaluated the effectiveness of cover crops for weed suppression in cropping systems, and these differences were largely due to cover crop and main crop management approaches used (Osipitan et al., 2018). Thus, there is a need to understand how these approaches could influence the effectiveness of cover crops for weed suppression. The current study is aimed at providing a quantitative review on how these management practices could influence the impact of cover crops on weed suppression through an analytical approach: meta-analysis. The adoption of meta-analysis for quantitative review is becoming more popular among agronomy researchers, as this approach provides a summarized quantitative estimate or information from data extracted through a comprehensive survey of previous studies (Egan et al., 2014; Pittelkow et al., 2015; Li et al., 2016; Himmelstein et al., 2017; Osipitan et al., 2018).

In particular, the current study uses meta-analysis to ask the following questions:

1. How does choice of cover crop species affect weed suppression?
2. How do cover crop management practices, such as sowing season or date, seeding rate, termination method, termination date, integrating cover crops with other weed control inputs, and tillage or cropping system adopted for cover crop production affect weed suppression at (i) cover crop termination or (ii) after main crop planting?

MATERIALS AND METHODS

Literature Search and Data Extraction

Data from previously published studies were used in the meta-analysis. Studies were identified in the Institute for Scientific Information (ISI) Web of Science database using search terms for nine different topics regarding weed suppression by using cover crops (Table 1). Terms used referred to (i) cover crop species, (ii) weed suppression or control as measured by weed biomass, density, and percentage control, (iii) cover crop termination method, (iv) cover crop termination timing, (v) tillage system in which cover cropping was practiced, (vi) cropping system in which cover cropping was practiced, (vii) cover crop seeding rate, (viii) season in which the cover crop was sowed, and (ix) whether cover crop was part of an integrated weed management program. The specific criteria for selecting a study included (i) study was conducted in the field, (ii) treatments were randomized with replications, (iii) results reported weed biomass, density, or percentage weed control after cover crop and no cover crop treatments, (iv) time of collecting weed data was specified, and (v) sufficient information was provided to estimate variance of mean values for weed biomass or density. Using these criteria, we selected 53 papers published from 1990 to 2018 (see Supplemental Table S1 for the list of studies and their corresponding topics). All searches were concluded on 13 Feb. 2018. If a study had datasets from two or more sites, the data from each site was included separately. In general, a dataset from an experimental site-year in a study was considered as an observation. Mean values, variance (or SD), and number of replicates for each observation were extracted.

Analysis of Data

All management practices relating to cover crops were considered as interventions, whereas those relating to weedy check, bare ground, stubble, or fallow were considered as controls. An initial step was to standardize the collected data. The effect of intervention on weed biomass was converted to grams per square meter, and the effect on weed density was converted to number per square meter. In the analysis, both the intervention and control treatment data had same unit of measure from each study. A total of 36 and 23 studies reported weed biomass and weed density, respectively, as weed suppression variables. An initial meta-regression analysis suggested that there was no differential response ratio between weed biomass and weed density for each of the evaluated interventions. Hence, the response ratios of each measure (biomass and density) with

Table 1. Summary statistics and number of studies of the meta-analyses. A *P* value <0.05 was significant for measurement. See Supplemental Table S1 for a list of studies and their measures. Response ratio (R^*) was the weighted mean for each group.

Topic	Group	No. of studies	R^*	95% CI†	Study heterogeneity (I^2)	*P* value of measure among group
					%	
Cover crop biomass	Weed biomass	18	0.21	0.09–0.27	79	<0.01
	Weed density	16	0.27	0.08–0.31	82	0.03
Cover crop type	Individual species	42	0.54	0.01–1.01	91	<0.01
Sowing season	Fall vs. spring	7	0.22	0.12–0.40	98	<0.01
Seeding rate	1 to 3×	3	0.19	0.11–0.34	56	<0.01
Termination	Method	10	0.46	0.39–0.54	52	0.47
	Surface or incorporated	5	0.41	0.38–0.51	65	0.71
Termination time	Earliness	4	0.35	0.27–0.46	68	0.05
	Crop planting date after termination	5	0.29	0.20–0.43	66	0.01
Tillage system	Conventional, reduced, or no-till	6	0.21	0.16–0.27	89	0.04
Cropping system	Sequential or intercropping	19	0.20	0.18–0.22	91	0.27
Integrated weed management	With or without herbicide	12	0.14	0.09–0.20	53	<0.01

† CI, confidence interval.

respect to their corresponding controls were pooled for each intervention. The meta-analysis required a value of the mean, SD, and number of replicates (n) for both intervention and control treatments. A next step was to calculate the natural log of response ratio (R) between intervention and control treatments (Hedges et al., 1999):

$$R = \ln(X_t/X_c) \quad [1]$$

where X_t and X_c are the mean values for intervention and control, respectively.

The variance (v) of R was given as

$$v = \frac{SD_t^2}{X_t^2 n_t} + \frac{SD_c^2}{X_c^2 n_c} \quad [2]$$

where subscripts "t" and "c" represent intervention and control, respectively.

The effect size (level of weed suppression) of each intervention was summarized using weighted mean of R ($R^\star$) between studies (or observations):

$$R^* = \frac{\sum_{i=1}^{k} w_i R_i}{\sum_{i=1}^{k} w_i} \quad [3]$$

where $w_i = 1/v_i$ (i.e., inverse variance of the ith study), and R_i was the R of the ith study.

The SE of the $R^\star$ adopted from Hedges et al. (1999) was given as

$$\mathrm{SE} = \sqrt{\left(\frac{1}{\sum_{j=1}^{k} w_j^*}\right)\left\{1 + 4\sum_{i=1}^{k}\frac{1}{\mathrm{df}_i}\left(\frac{w_i^*}{w_i}\right)^2 \frac{w_i^*\left[\left(\sum_{j=1}^{k} w_j^*\right) - w_i^*\right]}{\left(\sum_{j=1}^{k} w_j^*\right)^2}\right\}} \quad [4]$$

where w_i^* was the inverse of total variance of R_i, w_j^* was the inverse of the total variance of the correction factor, and df_i was the degree of freedom in the ith study.

Finally, the 95% confidence interval (CI) was calculated, with the lower limit (CI_L) of $R^\star$ given as

$$CI_L = R^\star - Z_{0.025}\mathrm{SE}(R^\star) \quad [5]$$

where $Z_{0.025}$ was the critical z value at $\alpha = 0.025$, whereas the upper limit (CI_U) was given as

$$CI_U = R^\star + Z_{0.025}\mathrm{SE}(R^\star) \quad [6]$$

A response ratio with CI ≥1 indicates that an intervention did not provide weed suppression (or resulted in increased weed presence), whereas a response ratio with CI <1 indicates that weeds were suppressed. Depending on the CI, the lower the response ratio, the greater the level of weed suppression. The difference in response ratio (or weed suppression) among interventions was evaluated using the bias-corrected 95% CI with random effect model: differences exist among interventions if $p < 0.05$. Meta-regression analysis was used to test the relationship between cover crop biomass and weed suppression as measured by weed biomass and density. Total heterogeneity in response ratio among studies comparing interventions was also evaluated using I^2 statistics (Higgins et al., 2003). The heterogeneity among studies was classified as low, moderate, or high if I^2 is ≤25%, around 50%, or ≥75%, respectively. Analyses were conducted utilizing R statistical software with "meta" package, version 3.4.1 (R Core Team, 2017).

RESULTS

Management Decisions as They Influenced Effectiveness of Cover Crops for Weed Suppression

Cover Crop Species and Biomass

The meta-analysis showed that there were differences in level of weed suppression at termination among cover crop species. The response ratio provided by cover crop species ranged from 0.06 (95% CI = 0.03–0.15) in cereal rye to 0.71 (95% CI = 0.48–1.09 and 0.34–1.11) in radish (*Raphanus raphanistrum* L.) and buckwheat (*Fagopyrum esculentum* Moench), respectively. In most cases, the grass cover crop species provided greater weed suppression than the broadleaf cover crop species (Fig. 1). All cover crops suppressed weeds at termination except blackmedic (*Medicago lupulina* L.), buckwheat, mustard (*Sinapis alba* L.), pea, radish, and sunflower (*Helianthus annuus* L). Cover crop biomass was inversely related to

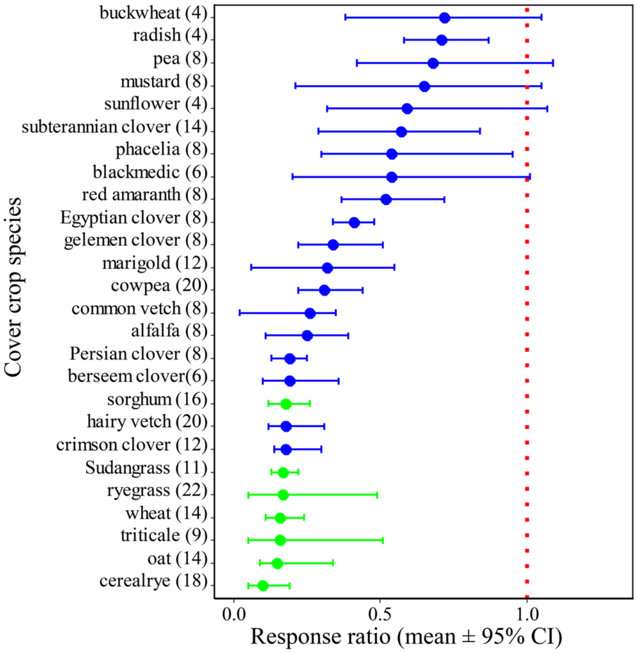

Fig. 1. Weed suppression provided by each cover crop species at termination up to 4 wk after termination. Species with blue and green color represent broadleaf and grass cover crops, respectively. The smaller the response ratio, the greater the level of weed suppression. The number of observations is shown in parentheses. The *P* value was <0.01. CI, confidence interval.

the level of weed biomass (r^2 = 0.67) and weed density (r^2 = 0.64); increase in cover crop biomass provided greater weed suppression (Table 1, Fig. 2). For example, biomass of cover crops established in fall reduced weed biomass ($R^\star$ = 0.21, 95% CI = 0.09–0.27) and weed density ($R^\star$ = 0.27, 95% CI = 0.08–0.31) by the summer (Table 1).

Sowing Season and Seeding Rate

Fall-sown cover crops provided greater weed suppression in the summer ($R^\star$ = 0.19, 95% CI = 0.09–0.38) than spring-sown cover crops ($R^\star$ = 0.48, 95% CI = 0.47–0.64) (Fig. 3). The heterogeneity among studies was high (I^2 = 98%). Seeding rates were classified into standard (1×), double (2×), and triple (3×) rates, as suggested by the primary studies of Brennan et al. (2009) and Ryan et al. (2011). For example, standard seeding rate for cereal rye in mid-Atlantic region

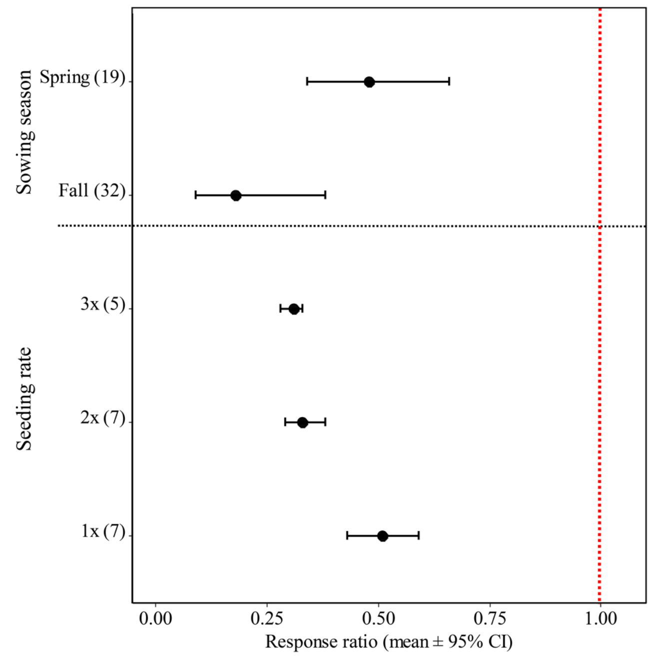

Fig. 3. Summer weed suppression provided by cover crops sown in fall vs. spring, and different seeding rates. Seeding rates were classified into standard (1×), double (2×), and triple (3×) rates, as suggested by the primary studies of Brennan et al. (2009) and Ryan et al. (2011). For example, the standard seeding rate for cereal rye in the mid-Atlantic region was 90 kg ha^{-1} (Ryan et al., 2011). Observations for sowing season were pooled up to 1 wk after cover crop termination, whereas observations for seeding rates were collected 3 to 6 wk after cover crop termination. The number of observations from studies is shown in parentheses. The *P* values for sowing season and seeding rate were significant at <0.01. CI, confidence interval.

was 90 kg ha^{-1} (Ryan et al., 2011). Cover crop seeding rate affected (P < 0.01) weed suppression, such that weed biomass and density were reduced by increasing seeding rate of cover crops from the 1× seeding rate ($R^\star$ = 0.50, 95% CI = 0.35–0.62) to 2× ($R^\star$ = 0.27, 95% CI = 0.25–0.32) or 3× ($R^\star$ = 0.10, 95% CI = 0.25–0.29).

Termination Method and Residue Placement

Cover crop termination methods had no differential impact on weed suppression by cover crop, with observations

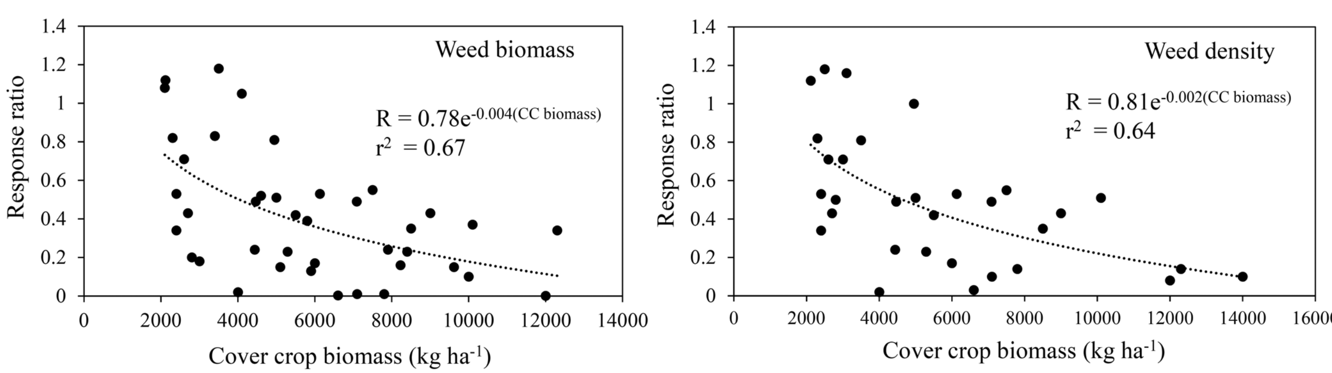

Fig. 2. Response ratio that describes the relationship between fall-sown cover crop (CC) biomass and suppression of weed biomass or weed density at termination in late spring or early summer.

pooled from 2 to 5 wk after termination (Table 1, Fig. 4). The termination methods included herbicide application, disking, mowing, rolling, or undercutting (Fig. 4). There was no difference in weed suppression if cover crop residue was incorporated into the soil after termination or cover crop residue was left on soil surface when observed at 2 to 5 wk after termination. Incorporating the terminated cover crop into the soil had a response ratio of 0.45 (95% CI = 0.38–0.54) vs. placing it on the soil with a response ratio of 0.49 (95% CI = 0.31–0.76).

Termination and Main Crop Planting Date

Weed suppression by cover crops terminated late was greater ($R^\star$ = 0.29, 95% CI = 0.21–0.45) than for those terminated early (2-wk interval; $R^\star$ = 0.74, 95% CI = 0.48–1.02) in spring (Table 1, Fig. 5). In addition, delayed crop planting by 1 to 4 wk after termination of cover crop increased the response ratio (i.e., less weed suppression) from 0.13 (95% CI = 0.06–0.27) to 0.74 (95% CI = 0.62–0.88) (Fig. 5).

Tillage System, Cropping System, and Herbicide Use

Cover crops provided greater weed suppression with reduced tillage ($R^\star$ = 0.19, 95% CI = 0.06–0.21) than with no tillage ($R^\star$ = 0.29, 95% CI = 0.22–0.39), with great heterogeneity (I^2 = 89%) among studies (Table 1, Fig. 6). There was no difference in early weed suppression (up to 5 wk after main crop planting) by cover crops when intercropped or in sequence with main crop (Fig. 6) and

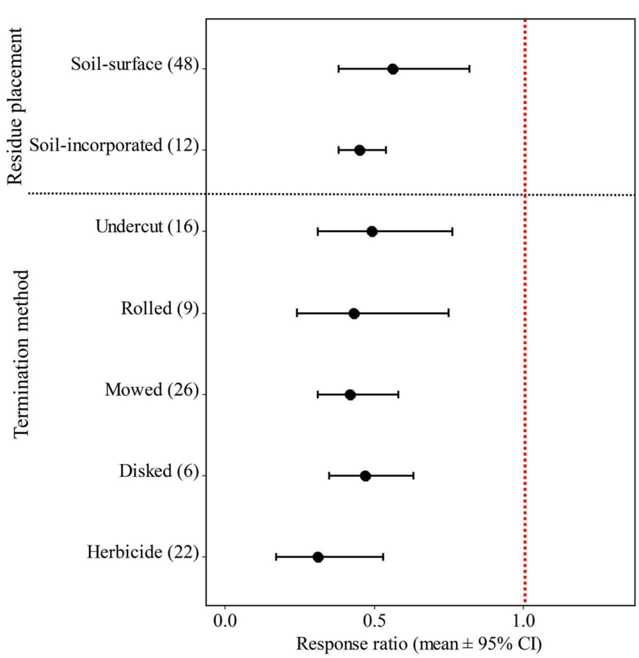

Fig. 4. Weed suppression provided by cover crops terminated by different methods and with different methods of residue placement. Observations were pooled 2 to 5 wk after cover crop termination. The number of observations from studies is shown in parentheses. The P values for termination and placement method were 0.47 and 0.71, respectively. CI, confidence interval.

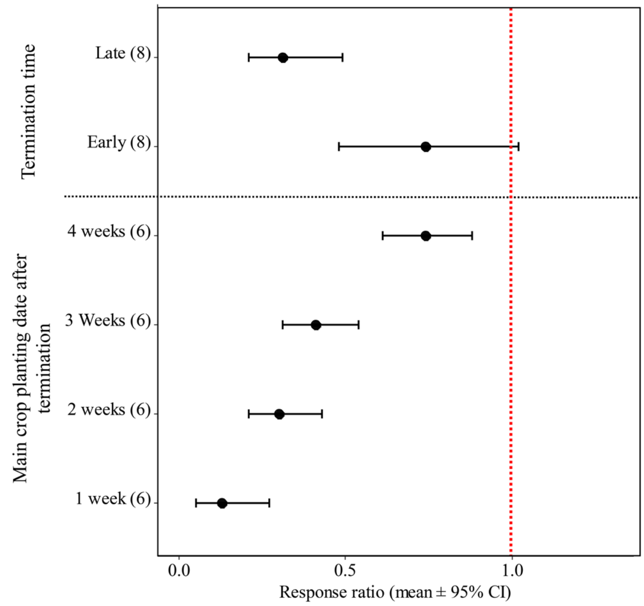

Fig. 5. Weed suppression provided by cover crop terminated at different times and the influence of delayed planting of main crops. There was at least 2 wk between the early and late termination times. Weed suppression observations were collected at 1 to 4 wk after cover crop termination, whereas weed suppression observations for planting date of main crop were pooled across 1 to 4 wk after planting. The number of observations from studies is shown in parentheses. The P values for termination time and main crop planting date were 0.05 and 0.01, respectively. CI, confidence interval.

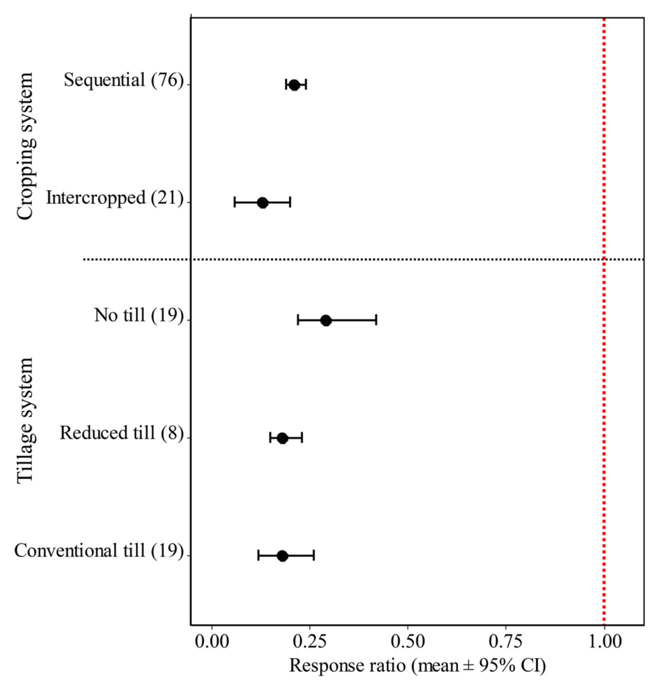

Fig. 6. Weed suppression provided by cover crops under different cropping and tillage systems. Weed suppression observations were collected 2 to 4 wk after main crop planting for cropping systems and at 3 to 6 wk after cover crop termination for tillage systems. The number of observations from studies is shown in parentheses. The P values for tillage and cropping systems were 0.04 and 0.27, respectively. CI, confidence interval.

there was great heterogeneity (I^2 = 91%) among studies (Table 1). Supplementing cover crops with residual or postemergence herbicides reduced weeds compared with only a single or mixed cover crop species (Table 1, Fig. 7).

DISCUSSION

Results showed that weed suppression provided by cover crops varies depending on management decisions as they relate to choice of cover crop species, seeding rate, sowing season, termination date, planting date of the main crop after cover crop termination, tillage system in which cover cropping was practiced, and whether cover crops will be integrated with other weed control practices. Among the cover crop species, the grass cover crops mostly provided greater weed suppression than the broadleaf cover crops based on observations made up to 4 wk after termination. The differential level of weed suppression by grass and broadleaf cover crops could be attributed to the inherent differences in their residue persistence, as the former mostly deteriorate slower (Ruffo and Bollero 2003; Mennan et al., 2006; Campiglia et al., 2012; Hayden et al., 2012). In addition, there are reported cases in which broadleaf (legume) cover crop residues stimulate weed emergence due to an increase in soil nitrate levels associated with legume decomposition after termination (Radicetti et al., 2013a). Our analysis showed that grass cover crops such as cereal rye, oat (*Avena sativa* L.), triticale (× *Triticosecale* Wittmack), wheat (*Triticum aestivum* L.), ryegrass (*Lolium multiflorum* Lam.), and sudangrass [*Sorghum* × *drummondii* (Nees ex Steud.) Millsp. & Chase] could provide 91 to 96% weed suppression compared with an uncontrolled weedy check, including bare ground (Fig. 1). Among broadleaf cover crops, hairy vetch (*Vicia villosa* Roth), as well as crimson, berseem (*Trifolium alexandrinum* L.), and Persian clover (*Trifolium resupinatum* L.) species, provided greater weed suppression (89%) than pea, radish, and buckwheat (32–41%), probably due to differential cover crop biomass and soil surface cover that impede weed seedling emergence (Teasdale et al., 1991; Radicetti et al., 2013a). However, it should be noted that the evaluation of these cover crop species was up to 4 wk after termination, and results could have varied if the evaluation period was earlier or beyond 4 wk after their termination. For example, a fall-sown radish provided excellent (100%) weed suppression in fall up to early spring before spring termination, but the suppression did not persist into the subsequent cropping season after termination due to rapid decomposition of residues (Lawley et al., 2011).

Our analysis showed that cover crop biomass productivity was an important index that could contribute to the differential weed suppression provided by the cover crop species. The individual data point used in the regression analysis was relative weed presence at different levels of cover crop biomass across 16 and 18 studies for weed density

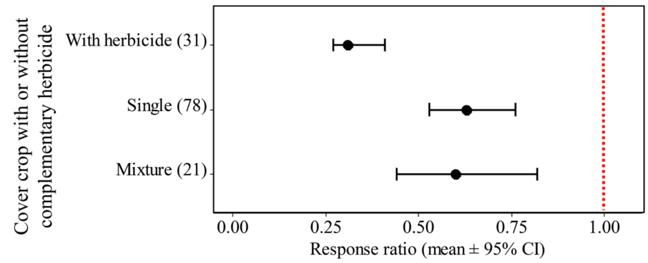

Fig. 7. Weed suppression provided by cover crop integrated with or without herbicide, based on observations collected 2 to 4 wk after planting of main crop. Cover crop species were either used singly or mixed. The number of observations from studies is in parentheses. The *P* values were <0.01. CI, confidence interval.

and weed biomass, respectively. This analytical approach provided an opportunity to evaluate weed suppression level provided by a range of cover crop biomass, which could be difficult for a single study to achieve. The more cover crop biomass, the greater the weed suppression. Cover crops such as cereal rye, oat, triticale, wheat, and hairy vetch have been shown to possess relatively great biomass productivity even with moderate seeding rates (Brennan and Smith, 2005; Smith et al., 2014; Petrosino et al., 2015). An important benefit of enhanced cover crop biomass is greater coverage of the soil surface by the residues, with a subsequent impact on reducing weed seed germination, as well as physically impeding weed seedling emergence (Teasdale and Mohler, 2000; Hayden et al., 2012). An increase in cover crop biomass could also lengthen the duration of weed suppression (Teasdale et al., 1991).

Superior weed suppression into the summer was provided by fall-sown cover crops compared with spring-sown cover crops, and this could be attributed to longer growing season for the cover crop biomass to accumulate (Petrosino et al., 2015). In addition, earlier sown cover crops would have a competitive advantage and achieve ground cover sooner to shade and reduce seedling emergence of summer annual weed species. It is well known that weed species emerging before or at the same time as the cover crop are more competitive than later emerging weeds (Dieleman et al., 1995). Simultaneous emergence and growth of spring-sown cover crops and weed species will probably not provide significant weed suppression by cover crops (Ngouajio and Mennan, 2005; Petrosino et al., 2015). Sowing date within each of the growing seasons (fall or spring) is also crucial in determining cover crop biomass accumulation and subsequent weed suppression. Anugroho et al. (2009) reported that an 8-wk delay in fall sowing date of hairy vetch cover crop led to biomass reduction of 840 to 2220 kg ha^{-1} with a consequent 40% increase in weed biomass in spring compared with a sowing date 8 wk earlier. Saini et al. (2006) reported a dramatic (≥42%) reduction in cover crop biomass production with a 1-wk delay in sowing a winter cover crop, and a corresponding reduction in summer annual weed suppression.

Increasing the seeding rate of the cover crop species is expected to reduce available niches for weed emergence and growth, increase the competitive advantage of living cover crops against weeds, and increase the production of cover crop biomass for weed smothering. Specifically, the analysis showed that doubling or tripling the seeding rate resulted in greater weed suppression than seeding at a rate considered as standard. For example, increasing the seeding rate of cereal rye resulted in 67% greater weed suppression when the cover crop was seeded at thrice the standard rate (Brennan et al., 2009).

Common cover crop termination methods, such as burndown by herbicide, disking, mowing, rolling, or undercutting by sweep-blade plow, had no differential impact on weed suppression caused by cover crops, based on assessment at 2 to 4 wk after termination of cover crops. However, the evaluated studies suggested that there could be confounding impact between the cover crop and its method of termination on weed suppression (Hoffman et al., 1993; Masiunas et al., 1995; Carrera et al., 2004). For example, the mowing method of termination resulted in less cover crop control and biomass but similar weed suppression to when the termination method was by rolling or herbicide burndown (Carrera et al., 2004), suggesting that weed suppression was not solely provided by the biomass of the cover crop residues but aided by the additional management practice. It is important to note that similar weed suppression reported with the termination method may not result in similar main crop yields. For example, cereal rye and hairy vetch terminated by mowing resulted in regrowth of the cover crop a few days after termination, causing competition with the main crop and consequent yield reductions (Masiunas et al., 1995; Carrera et al., 2004). In general, selection of the termination method should consider their effectiveness in cover crop control, and this may depend on the cover crop species.

When cover crops are terminated, the residues are usually placed on the soil surface in no-tillage systems or are incorporated into the soil in reduced or conventional tillage systems. Evaluating the differential impact of placing cover crop residue on the soil surface or incorporating into the soil on weed suppression was complicated because of the confounding impact of the placement process by the tillage systems. It is expected that a tillage process involving incorporation of the cover crop into the soil will, on its own, contribute to weed suppression even without a cover crop. The decision to incorporate cover crop residues into the soil is usually for soil health improvement and is not reflective of its importance for weed suppression. There are reported cases in which cover crops incorporated into the soil promoted weed growth. For example, Radicetti et al. (2013b) reported that the soil incorporation of hairy vetch residues by plowing caused greater weed biomass than observed when the hairy vetch residues were mowed and left on soil surface as dead mulch; the greater weed biomass was attributed to a stimulatory effect caused by high nitrogen availability from the mineralization process.

Our analysis showed that delaying termination of cover crops up to 2 wk in spring increased weed suppression after termination. Indeed, delaying termination would allow for more biomass accumulation, which is essential for weed smothering by the cover crop residues. For example, rye biomass increased by 37 to 100% when terminated 10 to 14 d after the normal early rye termination date, with subsequent increases in weed suppression (Mischler et al., 2010; Mirsky et al., 2011; Nord et al., 2012). The analysis further showed that delaying the planting date of the main crop after termination of the cover crop could reduce the level of weed suppression during the growing season. This is expected, as cover crop residue degrades gradually, thereby reducing it smothering ability over the main crop growing period. Early use of cover crop residue (i.e., early planting of the main crop into the cover crop residue) will potentially allow optimal utilization of its smothering ability.

Aside the common use of cover crop residues for weed suppression after termination, living cover crops are also used for weed suppression in main crops, as living mulch (Teasdale, 1996; Abdin et al., 2000; Uchino et al., 2015). Use of the cover crop as residue or living mulch in main crop is often practiced through sequential cropping or an intercropping system, respectively. The meta-analysis showed that the cover crops in these two cropping systems had no differential influence on the level of early weed suppression at 2 to 4 wk after planting the main crop. However, Teasdale (1996) suggested that a cover crop intercropped as a living plant with the main crop could inhibit germination and emergence of weeds better than a terminated cover crop in the sequential system. It should be noted that an intercropped cover crop could potentially compete with the main crop for limited resources, leading to impacts on main crop yield vs. when cover crop residue is used (Teasdale, 1996; Uchino et al., 2015). For this reason, several strategies have been suggested for reducing competitive effects, such as shifting the relative sowing date of intercropped species or providing supplemental inputs to compensate for limited resources (Campiglia et al., 2014).

The tillage system in which cover cropping was practiced influenced the use of cover crops for weed suppression. The meta-analysis showed greater weed suppression in reduced tillage than in no-tillage systems. However, the greater weed suppression recorded in the reduced tillage system could not be attributed solely to cover cropping. Cover crop residue should not be expected to reduce weed species in conventional tillage because residues are incorporated into the soil, rather than concentrated on the soil surface as in the case of no tillage (Teasdale 1996), except if the cover crop residues possess allelochemicals that could be released during decomposition to inhibit weed germination and growth (Tabaglio et al., 2013). Reports have shown that conventional or reduced tillage are more likely to reduce weed infestation than no-tillage systems (Teasdale, 1996; Pekrun and Claupein, 2004; Weber et al., 2017). Conversely, Radicetti et al. (2013a) reported that in a Mediterranean environment, the adoption of oat residues resulted in the same weed suppression level regardless of soil tillage system.

In general, weed suppression provided by cover crops can be complemented with herbicides with residual or foliar activities. Cover crops have been shown to provide satisfactory early weed suppression in many cropping systems, but not full-season weed control due to often insufficient biomass production and quick degradation of cover crop residues (Teasdale, 1996; Anugroho et al., 2009; Nord et al., 2012). Nord et al. (2012) reported 96% reduction in weed biomass at 12 wk after planting soybean [*Glycine max* (L.) Merr.] in cover crop plots complemented with postemergence herbicide, compared with plots with no postemergence herbicide application. Cover cropping could be used as a preplant and preemergence weed control input, and this would usually require postemergence inputs to provide season-long weed control necessary for optimum crop yield (Langeroodi et al., 2018). In addition, a report also showed that despite the ability of cover crops to provide early weed suppression, the absence of residual herbicide could allow a severe level of weed infestation later in the growing season (Teasdale 1996).

It is expected that environmental factors such as soil fertility and soil water level could influence cover crops and their ability to suppress weeds; however, these were not evaluated in this meta-analysis study, as there was a lack of primary studies that evaluated the influence of soil water on weed suppression by cover crops. A report showed that most studies that evaluated weed suppression by cover crops were conducted at sites with what appeared to be adequate annual rainfall (≥750 mm) or with irrigation provided where rainfall was inadequate to optimize cover crop biomass production necessary for weed suppression (Osipitan et al., 2018). However, a study showed that an increase (0 to 160 kg ha^{-1}) in soil nitrogen increased rye cover crop biomass, but no corresponding decrease in weed biomass was observed (Ryan et al., 2011).

CONCLUSION

An underlying principle for using cover crops to provide weed suppression is to maximize residue biomass and surface cover, and these could be influenced by the cover crop species and management decisions. In general, results showed that cover crops could provide a range of weed suppression, depending on management decisions such as choice of cover crop species, cover crop sowing season, sowing dates within seasons, seeding rate, termination date, delay in main crop planting date after cover crop termination, tillage systems, and integrating cover crops with herbicide for weed control. However, it is important to note that the interactive impact of these management decisions on the effectiveness of cover crops for weed suppression and main crop yield was not evaluated in this study; hence, the influence of management decisions on weed suppression should not be interpreted to mean a corresponding influence on main crop yield. The differential weed suppression provided by the evaluated management approaches suggested that cover crop management approach should be rightly selected for weed suppression benefit.

Conflict of Interest

The authors declare that there is no conflict of interest.

Supplemental Material Available

Supplemental material is available online for this article.

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