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Cover Crop for Early Season Weed Suppression in Crops: Systematic Review and Meta-Analysis

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ABSTRACT

Cover crops are gaining importance as their use has numerous benefits including improved soil health, reduced soil erosion, and weed suppression. Weeds are most competitive with crops at early growth stages, and a management strategy that ensures early season weed suppression in crops is crucial for crop growth, development, and yield. In this study, systematic and meta-analytic reviews of published studies from 1990 to January 2017 were conducted to provide evidence on whether using cover crops can provide satisfactory weed suppression at termination of the cover crop and up to 7 wk after planting of the main crop. The impact of cover crops as a weed control input on main crop yield was also evaluated. A total of 46 relevant field studies were evaluated. Main crops were planted 1 to 3 wk after termination of the cover crops. Overall, our meta-analysis results indicated that cover crops provided early season weed suppression comparable to those provided by chemical and mechanical weed control methods in cropping systems. The use of cover crops for early season weed suppression had no effect on main crop grain yields, but could increase vegetable crop yields when compared with no cover crop. Decisions about selecting cover crops species type (broadleaf or grass) or number (single or mixtures) were not as important as identifying cover crops with inherent characteristics that suppress weeds, such as high biomass productivity and persistent residue.

Core Ideas

- Cover crops can effectively suppress weeds after termination and up to early stage of crop growth.
- Use of cover crops for early season weed suppression did not affect grain crop yield, but improved yield of vegetable crops.
- Use of a single cover crop species provided early weed suppression similar to that of cover crop species mixtures.
- There were differences in cover crop and main crop management among studies that evaluated cover crop for weed suppression.

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WEEDS OCCURRING during early crop growth need to be removed because these are known to be most competitive with crops (Knezevic et al., 2002; Norsworthy and Oliviera, 2004; Tursun et al., 2016; Osipitan et al., 2016). Uncontrolled weeds at this early growth stage could cause irreversible and substantial crop yield losses (Knezevic et al., 2002, Adigun et al., 2014). If weeds are controlled at this time, crops can get a head start, achieve canopy closure, and compete effectively with later emerging weeds (Rajcan and Swanton, 2001).

Typical early season weed control options include pre-plant, pre-emergence, and early post emergence herbicide applications in no-till cropping systems or mechanical cultivation in tilled systems. Herbicides provide an easy and cost-effective way of controlling weeds in crops and result in increased crop vigor and yield. Conversely, they are also a potential threat to the environment (e.g., pesticides residues in surface and/or groundwater) and in some areas, the development of resistant weed biotypes has reduced the utility of herbicides. In tillage-based cropping systems, mechanical operations such as plowing, harrowing, disking, and cultivating are used. Tillage for weed control has been utilized for a long time (Abdin et al., 2000) as it reduces weed density. At the same time, weed seeds receive a brief exposure to sunlight, due to soil inversion after tillage that can trigger their germination. There are still concerns about the negative impact of tillage on soil health and topsoil erosion (Loaiza Puerta et al., 2018).

Cover crops have been documented to improve soil quality and minimize environmental degradation while providing a level of weed suppression in crops (Bachie and McGiffen, 2013; Norsworthy et al., 2007; Petrosino et al., 2015; Teasdale and Mohler, 2000). Cover crops can potentially provide an alternative tactic for control of herbicide-resistant weeds (Price et al., 2016; Wiggins et al., 2016). Reported weed suppression provided by cover crops has not been consistent, as it can range from 0% weed control (Galloway and Weston, 1996) to 98% control (Hayden et al., 2012), perhaps due to environmental, management, or inherent factors (Teasdale, 1996). Cover crops provide weed suppression either through competition (Mirsky et al., 2013), smothering (Hutchinson and McGiffen, 2000), or allelopathic activity (Barnes et al., 1987; Kunz et al., 2016). Cover crops can either be inter-seeded (Abdin et al., 2000;

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Abbreviations: CC, cover crop; MD, mean difference; NCC, no cover crop; WAP, weeks after planting or transplanting.

Uchino et al., 2015) or sown in rotation with the main crop (Burgos and Talbert, 1996; Petrosino et al., 2015). For example, a cover crop inter-seeded 3 wk after main crop emergence resulted in 59 and 75% weed biomass reduction in soybean [*Glycine max* (L.) Merr.] (Uchino et al., 2015) and corn (*Zea mays* L.) (Abdin et al., 2000), respectively. Cover crops reduced early season weed densities by 60 to 90% with no effect on crop yield when terminated 1 to 2 wk before planting of main crops (Teasdale, 1993; De Haan et al., 2016).

Concerns over satisfactory weed control by cover crops alone have limited adoption of cover cropping as an alternative or component of an integrated weed management system (Price and Norsworthy, 2013). Other factors limiting cover crop adoption are additional management and increased costs, particularly in seeding and termination (Vincent-Caboud et al., 2017; Zhou et al., 2017). Various studies have evaluated how cover crops could reduce weed density and biomass in some specific cropping systems. However, a robust review on whether cover crops can provide satisfactory early weed control comparable to conventional weed control methods such as tillage and herbicide across different crop production systems is needed.

Systematic reviews and meta-analyses are methods that have been widely used for quantitative research reviews (Miguez and Bollero, 2005; Kettenring and Adams, 2011; Basche et al., 2014; Egan et al., 2014; Shrestha et al., 2016). Systematic reviews ensure that a comprehensive survey of primary studies occurred, with a goal of reducing bias by appraising and synthesizing the surveyed studies based on a set of criteria to answer a review question (Uman, 2011; Ekong et al., 2015; Phan et al., 2015a). However, it should be noted that studies showing significant effect of treatments are more likely to be found in a survey of the literature than those studies showing no effects, as the former are more often submitted and accepted for publication than the later (Higgins et al., 2003).

Data extracted through a systematic review are summarized into single quantitative estimates or effect sizes by a statistical technique known as meta-analysis (Haddaway et al., 2015). These review methods can be beneficial because they rely on quantitative information and allow for testing of hypotheses that cannot be satisfactorily answered by a single study (Phan et al., 2015a).

In this study, a systematic review and meta-analysis were conducted to evaluate the relative impact of using cover crops (i) on weed biomass and density at termination of cover crop; (ii) on weed biomass, density, and percentage weed control through 7 wk after planting (WAP) of main crop (or after transplanting in vegetables); (iii) as a weed management practice on main crop yield; and (iv) on weed biomass, weed density, and main crop yield between cover crop types (broadleaf vs. grass) and mixtures (any combination of two or more cover crop species).

MATERIALS AND METHODS

Literature Search

The primary literature search was performed using the ISI Web of Science and Scopus databases using these terms: "(cover-crop OR rye OR vetch OR radish OR cowpea OR triticale) AND (weed OR weed-biomass OR weed-density OR weed-control) AND (crop OR legume OR cereal OR grain OR vegetable)." No language restriction was applied and years of publication were from 1990 to 2017. All searches were concluded on 6 Jan. 2017. Hand search of authors' collections of relevant peer-reviewed articles were also included. All citations located in the searches were entered into ProQuest RefWorks (Cambridge Information Group, Bethesda, MD). Duplicate references (where information about study setting/location, title, and the study period were the same for different articles) were removed, and abstracts obtained for all remaining citations.

Criteria for Including a Paper

1. Research results reported weed biomass, density, or percentage control following a cover crop (CC) and for another weed control option.
2. The other weed control option (no cover crop, NCC) was specified and could be use of herbicide or tillage for weed control. All physical weed control methods were grouped as tillage including weeding by hand or hoeing.
3. Time periods of evaluating weed control were indicated; specifically weed data collected at time of CC termination through to 7 WAP.
4. Studies conducted in field settings and treatments were randomized with replications.
5. Yield data for main crop following the use of cover crop for weed control might be reported; study was not excluded if no yield was reported.
6. Sufficient information was provided to estimate standard deviation (SD) of mean values for weed biomass, weed density, weed control (%), and/or main crop yield as treatment effects of CC and NCC.

Full articles were obtained for all abstracts that met these research criteria, and those abstracts that indicated such data existed. In some cases, study authors were contacted for clarification. The experimental designs of these studies were either randomized complete blocks or split-plot designs with three to eight replications. Year and location were considered as the true replication within each study, and then the standard deviation was estimated. The relevance screening form, data extraction, and assessment of quality of reporting form were created in a spreadsheet (Microsoft Excel, Microsoft Corp., Redmond, WA).

Data Analysis

All measurements from each study were standardized to common units. Weed biomass was reported in g m^{-2}, weed densities were in plants m^{-2}, and percentage weed control was in reference to non-treated weedy check. Main crop yield was reported in kg ha^{-1}. As an initial step, a meta-regression analysis was conducted to determine whether (i) use of herbicide and tillage, (ii) crop production system (grain or vegetable crop), (iii) location of study (Asia, Europe, North America, and South America).

In this meta-analysis, effect sizes were summarized with mean differences between the effect of CC and NCC on each weed response variable and on main crop yield. A random-effects model was used, as it takes into account the diversity in factors that could influence primary treatment effects associated with study location, management practices, and cropping system. Weed suppression measures were classified into subgroups (weed biomass and weed density), whereas percentage weed control was analyzed separately in the meta-analysis. Cropping systems (main crops) were grouped into grain crops or vegetables in the meta-analysis. Higgins I^2 statistic was used to estimate the percentage of total variation in mean difference across the studies in each subgroup and overall, owing to heterogeneity rather than chance, with $p < 0.05$ considered as substantial heterogeneity. Mean difference within group was considered significant if the 95% confidence interval (CI) did not contain zero (null hypothesis). Overall mean difference was determined with Z-test and differences existed if $p < 0.05$.

Mean differences between CC and NCC on weed biomass, weed density, percentage weed control, and on main crop yield were presented with forest plots (Borenstein et al., 2009). The forest plot summarized the meta-analysis by showing if the overall or subgroup effect was based on many studies or a few, and to show whether studies varied substantially (Borenstein et al., 2009).

The differences between CC and NCC were evaluated for weed biomass and density at termination of cover crop and up to 7 WAP of main crop. The comparison to NCC at termination of CC was in reference to fallow or bare land (collectively called fallow), whereas comparison to NCC after planting of main crop was in reference to herbicide or tillage. The differential influence of type of CC (broadleaf and grass) or of single (one) vs. mixed (more than one) CC species on weed biomass and density and on main crop yield were evaluated. Analyses were conducted with "meta" package in R version 3.4.1 (R Core Team, 2017).

RESULTS

From initial searches, 894 potentially relevant studies, all written in English, were identified (882 from databases and 12 from hand-search; Fig. 1). After primary screening of titles and abstracts, 77 studies were selected for full-text screening. A total of 46 relevant studies satisfied inclusion criteria and provided enough information for estimation of standard deviation of the response variables (see Appendix A). Of the 46 studies, 36 were conducted in North America, 6 in Europe, 3 in Asia, and 1 in South America. Studies from the United States alone accounted for 72% of the total studies used for this review (Fig. 2A). Of the total studies, 94% planted cover crops in the fall, whereas 6% planted cover crops in the spring. These cover crops were terminated mechanically (70% of studies) or with herbicides (30% of studies). Herbicides used for terminating the cover crop were either residual or non-residual, with non-residual accounting for 96% of cases. The performance of cover crop terminated with residual herbicides was only evaluated at termination to avoid confounding effect of these herbicides during the main crop growing season. Main crops were planted within 1 to 3 wk after termination of cover crop. Tillage and herbicide as NCC treatments were reported in 70 and 30% of the studies, respectively (Fig. 2B). Of the total studies, two reported inter-seeding cover crop with main crop.

Some level of weed control by using a cover crop was measured in 32 studies by weed biomass, 18 studies by weed density, and 4 studies by percentage weed control, whereas 25 studies reported main crop yields (Fig. 3). Corn yield was reported in 21% of all studies and was the most reported main crop (Table 1). Hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.) were the most reported broadleaf and grass cover crop species, respectively (Table 1). Some of the important broadleaf weeds studied were redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), Palmer amaranth [*Amaranthus palmeri* (S.) Wats.], and velvetleaf (*Abutilon theophrasti* Medik.). Dominant grass weeds were green foxtail [*Setaria viridis* (L.) Beauv.], large crabgrass

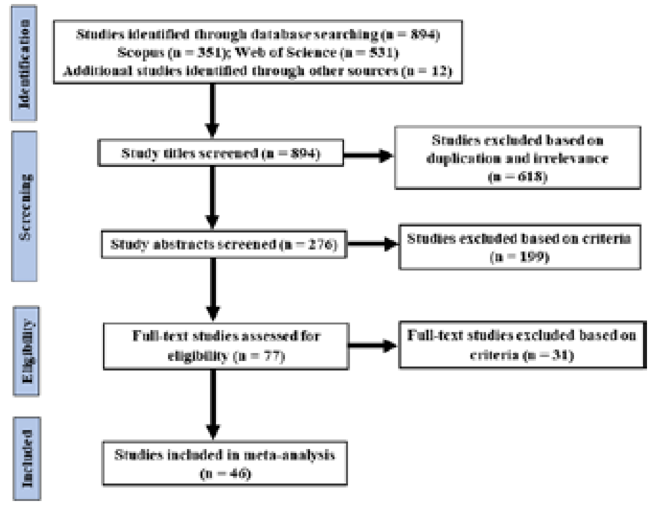

Fig. 1. Selection of studies for inclusion in the meta-analysis.

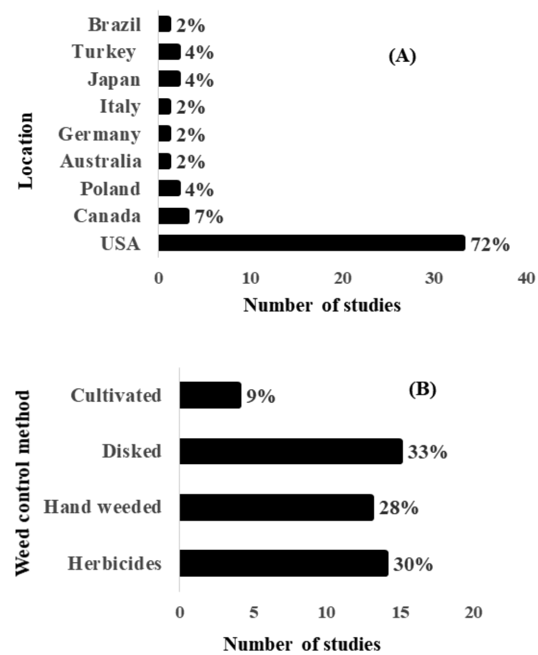

Fig. 2. Location of study and weed control methods reported in the articles used for the meta-analysis.

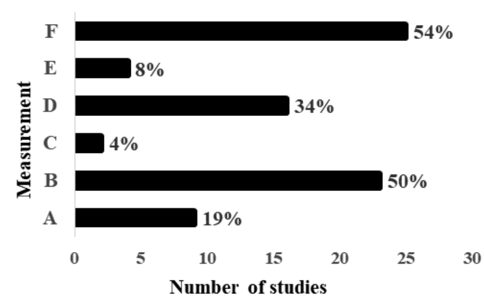

Fig. 3. The outcome measurements used in the meta-analysis. A: weed biomass at termination of cover crop, B: weed biomass up to 7 wk after planting (WAP) of main crop, C: weed density at termination of cover crop, D: weed density up to 7 WAP of main crop, E: percentage weed control up to 7 WAP, F: main crop yield.

Table 1. Type of cover crop (top 20), weed species (top 20), and main crops in the studies used for the meta-analysis.†

Cover crop	No. of studies	Weed species	No. of studies	Main crop	No. of studies
	%		%		%
Broadleaf:		Broadleaf:		Grain:	
Hairy vetch	13 (25)	Redroot pigweed	16 (33)	Corn	11 (21)
Crimson clover	8 (15)	Common lambsquarters	8 (15)	Soybean	5 (10)
Radish	8 (15)	Palmer amaranth	7 (14)	Rice	1 (2)
White mustard	6 (12)	Velvetleaf	7 (14)	Wheat	1 (2)
Common vetch	6 (12)	Waterhemp	6 (12)	Cowpea	1 (2)
Subterraneum clover	5 (10)	Purslane	6 (12)		
Alfalfa	2 (4)	Henbit	6 (12)	Vegetable:	
		Horseweed	6 (12)	Lettuce	2 (4)
Grass:		Black nightshade	6 (12)	Pepper	2 (4)
Cereal rye	14 (27)	Eastern black nightshade	5 (10)	Tomato	2 (4)
Oat	9 (17)	Prostrate knotweed	4 (8)	Collard	1 (2)
Annual ryegrass	6 (12)	Curly dock	4 (8)		
Triticale	6 (12)	Common morning-glory	4 (8)	Cucumber	1 (2)
Wheat	5 (10)	Field bindweed	4 (8)		
Barley	3 (6)				
		Grass and sedges:			
		Green foxtail	9 (17)		
		Large crabgrass	7 (14)		
		Bermudagrass	7 (14)		
		Yellow nutsedge	6 (12)		
		Perennial ryegrass	6 (12)		
		Barnyardgrass	6 (12)		

† Alfalfa, *Medicago sativa* L.; annual ryegrass, *Lolium multiflorum* Lam.; barley, *Hordeum vulgare* L.; barnyardgrass, *Echinochloa crusgalli* (L.) Beauv.; bermudagrass, *Cynodon dactylon* (L.) Pers.; black nightshade, *Solanum nigrum* L.; cereal rye, *Secale cereale* L.; collard, *Brasica olerecea* (Acephala Group); common lambsquarters, *Chenopodium album* L.; common morning-glory, *Ipomoea purpurea* (L.) Roth; common vetch, *Vicia sativa* L.; corn, *Zea mays* L.; cowpea, *Vigna unguiculata* (L.) Walp.; crimson clover, *Trifolium incarnatum* L.; cucumber, *Cucumis sativus* L.; curly dock, *Rumex crispus* L.; eastern black nightshade, *Solanum ptycanthum* Dunn; field bindweed, *Convolvulus arvensis* L.; green foxtail, *Setaria viridis* (L.) Beauv.; hairy vetch, *Vicia villosa* Roth; henbit, *Lamium amplexicaule* L.; horseweed, *Conyza canadensis* (L.) Cronq.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; lettuce, *Lactuca sativa* L.; oat, *Avena sativa* L.; Palmer amaranth, *Amaranthus palmeri* (S.) Wats.; pepper, *Capsicum annuum* L.; perennial ryegrass, *Lolium perenne* L.; prostrate knotweed, *Polygonum aviculare* L.; purslane, *Portulaca oleracea* L.; radish, *Raphanus sativus* L.; redroot pigweed, *Amaranthus retroflexus* L.; rice, *Oryza sativa* L.; soybean, *Glycine max* (L.) Merr.; subterraneum clover, *Trifolium subterraneum* L.; tomato, *Lycopersicon esculentum* L.; triticale, x *Triticosecale* Wittmack; waterhemp, *Amaranthus tubaculatus* Moq.; wheat, *Triticum aestivum* L.; velvetleaf, *Abutilon theophrasti* Medik.; white mustard, *Sinapis alba* L.; yellow nutsedge, *Cyperus esculentus* L.

Table 2. Meta-regression coefficients (b) and P-values indicating the influence of no cover crop (NCC) method, crop production system, and region of study on mean difference between cover crop (CC) and NCC on weed measures from termination to 7 wk after planting main crop, and main crop yield. b is significant if $P < 0.01$.

		Weed biomass		Weed density		% Weed control		Main crop yield	
Moderators	df	b	P-value	b	P-value	b	P-value	b	P-value
NCC method (herbicide vs. tillage)	1	800	0.176	803	0.901	908	0.624	631	0.389
Crop production system (grain vs. vegetable)	1	651	0.201	719	0.420	843	0.113	3210	0.004
Region of study (USA vs. others)	1	701	0.024	651	0.037	912	0.273	2041	0.001
Precipitation (≤500 mm vs. >500 mm)	1	967	0.511	239	0.071	–†	–	2453	0.098

† Not estimated.

[*Digitaria sanguinalis* (L.) Scop.], and bermudagrass [*Cynodon dactylon* (L.) Pers.] (Table 1).

An initial meta-regression analysis showed that comparing use of CC to herbicide or tillage separately had no differential influence on the effect size or mean difference for weed biomass, weed density, percentage weed control, and main crop yield (Table 2). Hence, herbicide and tillage treatments from the primary studies were grouped as NCC. The crop production system and location of study influenced the mean difference for main crop yield. Location of study influenced the effect sizes of weed biomass and density (Table 2). Annual precipitation of study locations ranged from 100 to 1600 mm. For example, studies on cover crop and weed suppression in corn and soybean were conducted in locations with annual precipitations >750 mm (see Appendix B).

Weed Suppression with Cover Crops

At termination of CC prior to planting of the main crop, there was an overall mean difference (MD) between CC and NCC on both weed biomass (MD = −42.94 g m^{-2}; 95% CI = −84.74 to −1.14; $P < 0.01$) and weed density (MD = −6.15 plants m^{-2}; 95% CI = −9.42 to −2.89; $P < 0.01$), with an overall

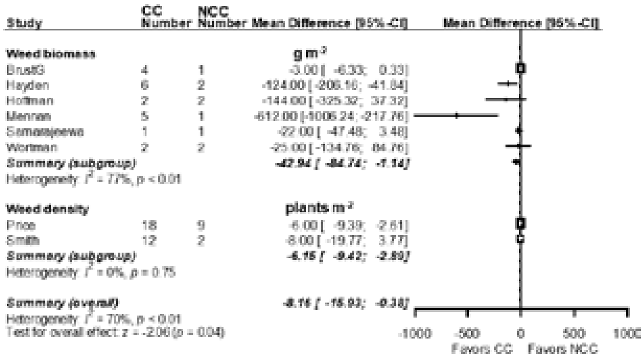

Fig. 4. Forest plot comparing cover crop (CC) and no cover crop (NCC) in terms of weed biomass and weed density at termination of cover crop using random effect model.

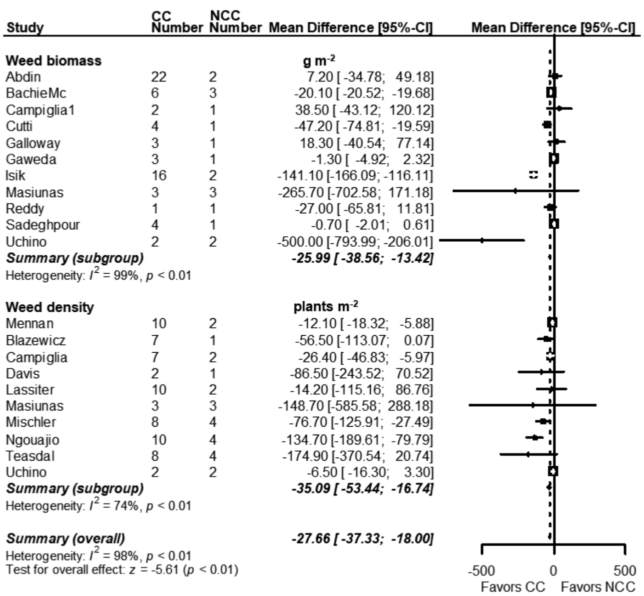

Fig. 5. Forest plot comparing cover crop (CC) and no cover crop (NCC) in terms of weed biomass and weed density up to 7 wk after planting of main crop using random-effects model.

beneficial impact on weed suppression (MD = −8.16; 95% CI = −15.93 to -0.38; $P < 0.01$). Overall, there was significant heterogeneity ($I^2 = 70\%$) among studies (Fig. 4). Subgroup analysis showed significant heterogeneity ($I^2 = 77\%$) among studies that measured weed biomass, but no significant heterogeneity among studies that measured weed density (Fig. 4). For example, among studies that measured weed biomass, four out of the six studies showed no significant difference between CC and NCC.

The overall mean difference for weed biomass and density in the presence of CC during the early part of the growing season, up to 7 WAP of main crop, were reduced when compared with NCC (MD = −27.66; 95% CI = −37.33 to −18.00; $P < 0.01$), with significant heterogeneity ($I^2 = 99\%$) among studies (Fig. 5). Specifically, weed biomass was reduced by CC compared with NCC (MD = −25.99 g m^{-2}; 95% CI = −38.56 to −13.42), with significant heterogeneity ($I^2 = 99\%$) among studies, such that 8 of the 11 studies were at variance with the summarized effect. Weed density was reduced by CC more than NCC (MD = −35.09 plants m^{-2}; 95% CI = −53.44 to −16.74). There was significant heterogeneity ($I^2 = 74\%$) among studies that reported weed density, with 6 out of the 10 studies indicating no significant difference between CC and NCC. Cover crop

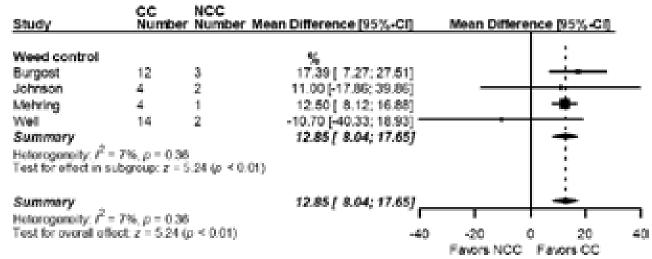

Fig. 6. Forest plot comparing cover crop (CC) and no cover crop (NCC) in terms of percentage weed control up to 7 wk after planting of main crop using random-effects model.

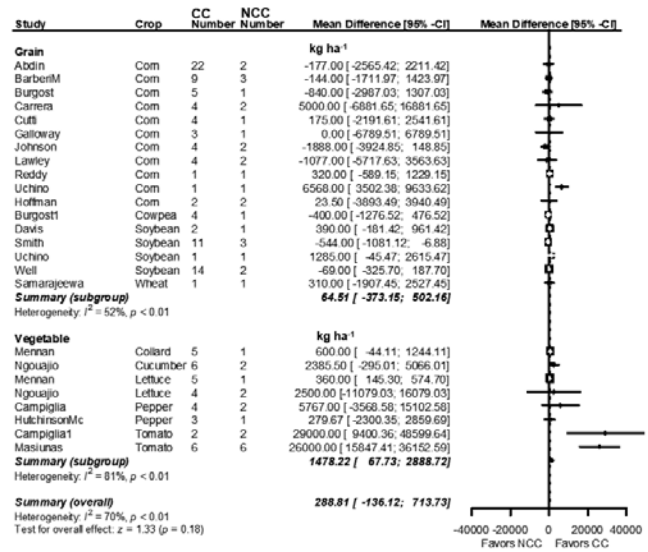

Fig. 7. Forest plot comparing cover crop (CC) as a weed control input and no cover crop (NCC) in terms of crop production system using random-effects model.

had greater percentage weed control for 7 WAP of main crop compared with NCC (MD = 12.85%; 95% CI = −8.04–17.65; $P < 0.01$), with no heterogeneity among studies (Fig. 6).

Relative Impact of Cover Crop as a Weed Control Practice on Main Crop Yield

Crop production systems were broadly grouped into grain and vegetable crops (Fig. 7). Overall, there was no difference in main crop yield between CC as a weed control practice and NCC, with overall significant heterogeneity ($I^2 = 70\%$) among studies, but these differences were not maintained in subgroup (crop class) analysis (Fig. 7). In grain (corn, cowpea [*Vigna unguiculata* (L.) Walp.], soybean, and wheat [*Triticum aestivum* L.]), there was no difference between CC and NCC on yields, whereas in vegetable crops (collard [*Brasica olerecea* (Acephala Group)], cucumber [*Cucumis sativus* L.], lettuce [*Lactuca sativa* L.], pepper [*Capsicum annuum* L.], and tomato [*Lycopersicon esculentum* L.]), greater main crop yields were obtained with CC compared with NCC (MD = 1478 kg ha^{-1}; 95% CI = 67–2888), with significant heterogeneity ($I^2 = 81\%$) among studies (Fig. 7).

Impact of Type of Cover Crop and Mixture on Weed Suppression and Crop Yield

A mixture of CC species reduced weed biomass (MD = −41.0 g m^{-2}; 95% CI = −50.14 to −31.86) and weed density (MD = −39.0 plants m^{-2}; 95% CI = −68.15 to −9.85) compared

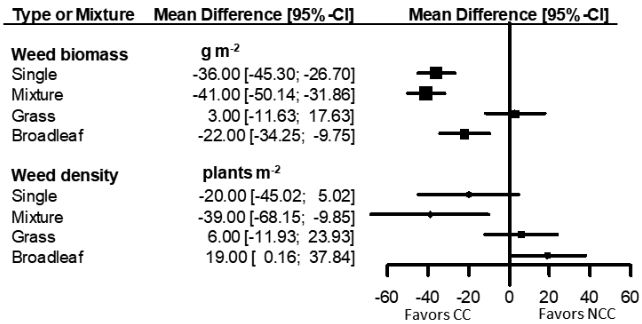

Fig. 8. Forest plot showing the differential influence of cover crop type (broadleaf, grass) and mixture (any combination of cover crop species) on weed biomass and weed density using random-effects model.

with NCC when measured up to 7 WAP (Fig. 8). Similarly, the use of a single species of CC compared with NCC reduced weed biomass (MD = –36.0 g m^{-2}; 95% CI = −45.30 to –26.70) but not weed density (MD = –20.0 plants m^{-2}; 95% CI = −45.02–5.02) for the same period of observation. Broadleaf CC species reduced weed biomass (MD = –22.0 g m^{-2}; 95% CI = –34.25 to −9.75) but not weed density when compared with NCC up to 7 WAP. A grass CC species compared with NCC had no difference in weed biomass and density (Fig. 8).

A mixture of CC species reduced yield for grain crops (MD = –1100 kg ha^{-1}) compared with NCC, but this reduction was not significant (95% CI = −5662–3462), whereas vegetable crop yields were greater (MD = 5900 kg ha^{-1}; 95% CI = 3939–7861) with mixture of CC species (Fig. 9). Sowing a single CC species compared with NCC resulted in greater main crop yields for vegetable crops, compared with NCC, but not for grain crops. Broadleaf or grass CC species compared with NCC produced greater vegetable crop yields (MD = 2900 kg ha^{-1}; 95% CI = 307–5493) but not grain crop yields (Fig. 9).

Specific impacts of CC type (broadleaf vs. grass) on corn (a grass crop) and soybean (a broadleaf crop) yields were evaluated (Fig. 10). Analysis showed that there was no difference in CC type on corn and soybean yield compared with NCC

DISCUSSION

A weed management strategy that ensures early season weed suppression in crops would help make available the limited resources that are crucial for crop growth, development, and yield. This systematic review and meta-analysis demonstrated that (i) cover crops can provide weed suppression at termination and up to early stages of main crop growth; (ii) use of cover crops for early weed suppression did not affect yields of grain crop, but improved yield of vegetable crops; (iii) single or mixtures of cover crop species provided similar levels of early weed suppression; (iv) grass and broadleaf cover crop species were both effective in providing early weed suppression; (v) a single or mixture of cover crop species compared with NCC had greater vegetable crop yields; and (vi) use of broadleaf or grass cover crop species compared with NCC increased vegetable crop yields.

Weed suppression by using cover crops is gaining more attention in reduced and no tillage systems, in particular as an increasing number of weed species are evolving resistance to herbicides (Petrosino et al., 2015; Oliveira et al., 2017; Osipitan and Dille, 2017). Previous research has shown that early season

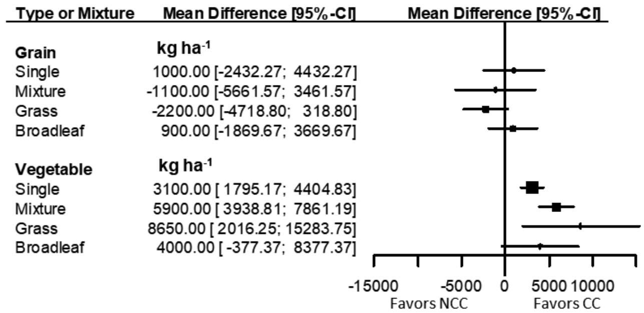

Fig. 9. Forest plot showing the differential influence of cover crop type (broadleaf, grass) and mixture (any combination of cover crop species) used for weed control on main crop yield using random-effects model.

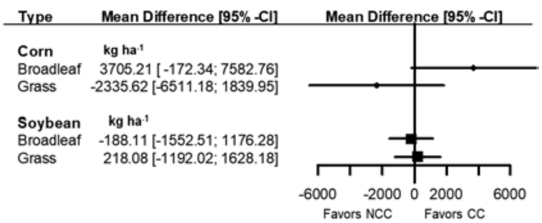

Fig. 10. Forest plot showing the differential influence of cover crop type (broadleaf, grass) and mixture (any combination of cover crop species) used for weed control on corn and soybean yield using random-effects model.

weed suppression by using cover crops with conservation tillage systems is comparable to chemical and mechanical control (Teasdale and Mohler, 1992; Johnson et al., 1993). The degree of weed suppression provided by a cover crop depends on persistence of its residue, surface cover, and cover and main crop management strategies (Saini et al., 2006; Campiglia et al., 2014).

Reported mechanisms by which cover crops suppress weeds include modification of soil microclimate (Stigter, 1984), inhibition of light penetration through cover crop residues (Creamer et al., 1996), physically impeding weed seedling emergence through cover crop residues (Teasdale and Mohler, 2000), competition with weeds for resources by living cover crops (Hartwig and Ammon, 2002; Teasdale et al., 2007), and by selective allelopathic activity (Weston, 1996; Caamal-Maldonado et al., 2001).

Because cover crops provide weed suppression, our analysis showed that they did not significantly affect main crop yield, and in vegetable crops yields were improved compared with no cover crop. Although there were reported cases in which cover crop residues or inter-seeded cover crops reduced main crop plant stands (4–13%; Teasdale, 1993; Saini et al., 2006; Uchino et al., 2015), the reduced stands did not adversely affect crop yields. Liebert et al. (2017) projected that soybean stands may decrease by 29,100 plants ha^{-1} for every 1 Mg ha^{-1} increase in cover crop biomass.

Use of cover crops for weed suppression in dry conditions could potentially reduce main crop growth and yield. Cover crops growing into May have resulted in soil water depletion, especially when spring rainfall was below normal (Clark et al., 1997; Wells et al., 2016). In addition, inadequately terminated cover crop will continue to deplete the limited soil water at the detriment of the main crop (Nielsen et al., 2016).

Cover crop residues persist long enough to provide weed suppression during the shorter growing season for transplanted vegetable crops (32–61 d) compared with the longer growing season for grain crops (75–130 d). Within this short growing season of vegetable crops after transplanting, cover crop residues still have adequate amount of biomass and surface cover to reduce weed biomass and density at the critical stages of weed competition (Teasdale, 1996; Ngouajio and Mennan, 2005; Campiglia et al., 2014; Korres and Norsworthy, 2015). As cover crops provide weed suppression, legume cover crops may supply N into the soil, which promotes main crop growth and yield (Ngouajio and Mennan, 2005).

Early season weed suppression with cover crops did not depend on whether it was a mixture or a single cover crop species. This was similar to reports by Brust and Gerhards (2012), Halde et al. (2014), Smith et al. (2014), and Licht et al. (2016). An underlying principle for using cover crops to provide weed suppression is to maximize residue biomass and surface cover, and this is not necessarily guaranteed by cover crops in a mixture (Brennan and Smith, 2005; Hayden et al., 2012; Gawęda et al., 2014; Smith et al., 2014; Nielsen et al., 2015), whereas in some cases, a single species provided similar or more biomass compared with a mixture (Hayden et al., 2012; Gawęda et al., 2014; Mehring et al., 2016; Liebert et al., 2017). For example, a rye cover crop and its mixture with hairy vetch with at least 330 and 364 g m^{-2} aboveground biomass, respectively, equally provided weed biomass suppression ranging from 95 to 98% (Hayden et al., 2012).

Our analysis showed that a mixture of cover crop species for weed suppression improved vegetable crop yields, but may potentially reduce grain yields. Reports have shown that enhanced residue biomass provided by a cover crop mixture may result in poor main crop establishment, reduced early crop growth, and in some cases a net loss in yield (Liebl et al., 1992; Nielsen et al., 2016; Liebert et al., 2017). An intermediate cover crop residue biomass (e.g., 5100 kg ha^{-1} compared with 3400 and 6800 kg ha^{-1}) was proven to maximize crop yield (Wicks et al., 1994).

There was heterogeneity among studies for most measurements of weed suppression and main crop yield. For example, 60% of the primary studies were at variance with the summarized effect between cover crop and no cover crop on weed suppression. This was not unexpected in a meta-analysis study (Phan et al., 2015b). Some research studies were conducted with more replications within a year, over years, and across location with less variance than others (see Fig. 4 and 5). Hence, a conclusion that comes from a less replicated study with high variance weigh less than a study with more replications and less variance.

In addition, heterogeneity was expected as these field studies were conducted across different agronomic and environmental conditions around the world. Our analysis confirmed that differences in location of study could be a source of heterogeneity. Studies within the United States, which accounted for 72% of the literature used for this study, also showed substantial heterogeneity for most measurements when studies from other locations where excluded, suggesting that there may be other sources of heterogeneity. Annual precipitation associated with each study location did not influence the effect sizes, as suggested by the meta-regression analysis. Most of the studies were conducted at locations with annual precipitation >750 mm, which appears to be adequate for crop growth. If locations had annual precipitation <500 mm, studies were conducted using irrigation (Hutchinson and McGiffen, 2000; Ngouajio et al., 2003). The main sources of heterogeneity could be differences in cover crop management, such as species used (e.g., cereal rye vs. radish [*Raphanus sativus* L.]), time of seeding, fertilization practices, method of termination, time between cover crop termination and main crop planting, among others. As a next step, a study by these authors will be evaluating how these management practices could influence effectiveness of using cover crops for weed management. To address differences among the primary studies, a random-effects model was used for the meta-analysis. This model recognized the variance among studies, and summarized the effect sizes as weighted means based on these differences. Generally, there are differences between the sample sizes of the CC and NCC, with CC in most cases having higher sample sizes. This was addressed by the meta-analysis, as the confidence interval of a mean difference took account not only of the total sample size, but also the sample size in each cover crop and no cover crop (Borenstein et al., 2007).

CONCLUSION

Our review showed that there were diverse approaches in studies that measured weed suppression by cover crops in crop production systems. A review of these studies showed various factors relating to cover crops and main crop management, as well as inherent characteristics of the cover crops that could influence effectiveness of cover crops for weed control. Efforts should be made to understand how these management practices could influence the use of cover crops in weed control. This review showed that cover crops could provide early weed control comparable to those provided by chemical and mechanical weed control methods in cropping systems. The presence of cover crops for early weed control could help to increase vegetable crop yield when compared to no cover crops. Decision to use cover crops as a mixture, single, grass, or broadleaf is not as important as selecting cover crops based on their inherent characteristics that suppress weeds. Some of these characteristics based on literature review are high biomass productivity and persistent residue.

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APPENDIX A

Articles used for the systematic review and meta-analysis.

	Measurements			
Authors	Weed biomass	Weed density	% Weed control	Crop yield†
Abdin et al., 2000	X			corn
Bachie and McGiffen, 2013	X			
Barberi and Mazzoncini, 2001	X	X		corn
Błażewicz-Woźniak et al., 2015		X		
Brainard et al., 2008	X			
Brennan and Smith, 2005		X		
Brust and Gerhard, 2012	X			
Burgos and Talbert, 1996			X	corn
Butler et al., 2016		X		
Campiglia et al., 2010	X	X		tomato
Campiglia et al., 2012	X			pepper
Campiglia et al., 2014	X			corn
Carrera et al., 2004	X			corn
Hutchinson and McGiffen, 2000	X			pepper
Curran et al., 1994	X	X		corn
Cutti et al., 2016	X	X		corn
Davis, 2010	X	X		soybean
Galloway and Weston, 1996	X			corn
Gawęda et al., 2014	X			
Halde et al., 2014	X			
Hayden et al., 2012		X		
Hoffman et al., 1993	X			corn
Isik et al., 2009	X			
Johnson et al., 1993			X	corn
Reddy and Koger, 2004	X			
Lassiter et al., 2005		X		
Lawley et al., 2011	X			
Lawson et al., 2015			X	
Masiunas et al., 1995	X	X		tomato
Mehring et al., 2016			X	
Mennan et al., 2006	X			lettuce
Mirsky et al., 2013	X			
Mischler et al., 2010		X		
Ngouajio and Mennan, 2005		X		lettuce
Ngouajio et al., 2003	X			cucumber
Nord et al., 2012	X			
Price et al., 2016		X		cotton
Sadeghpour et al., 2014	X			
Samarajeewa et al., 2005	X			wheat
Smith et al., 2014	X			
Smith et al., 2015		X		soybean
Teasdale et al., 1991	X	X	X	
Uchino et al., 2009	X	X		corn, soybean
Uchino et al., 2015	X	X		corn, soybean
Wells et al., 2016			X	soybean
Wortman et al., 2013	X			

† Corn, *Zea mays* L.; cotton, *Gossypium hirsutum* L.; cucumber, *Cucumis sativus* L.; lettuce, *Lactuca sativa* L.; pepper, *Capsicum annuum* L.; soybean, *Glycine max* (L.) Merr.; tomato, *Lycopersicon esculentum* L.; wheat, *Triticum aestivum* L.

APPENDIX B

Location of the study and annual rainfall (at the year of study) for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.].

Authors	Crop†	Study location	Precipitation, mm
Abdin et al. 2000	Corn	Quebec, Canada	755
Barberi and Mazzoncini, 2001	Corn	Central Italy	901
Burgos and Talbert, 1996	Corn	Fayetteville, AR	1000
Carrera et al., 2004	Corn	Beltsville, MD	1000
Cutti et al., 2016	Corn	RS, Brazil	800
Galloway and Weston, 1996	Corn	Lexington, KY	1050
Hoffman et al., 1993	Corn	Columbus, OH	1450
Johnson et al., 1993	Corn	Columbia, MO	1000
Lawley et al., 2011	Corn	Beltsville, MD	950
Reddy and Koger, 2004	Corn	Stoneville, MS	1400
Uchino et al., 2015	Corn	Saporo, Japan	1100
Davis, 2010	Soybean	Urbana, IL	975
Smith et al., 2014	Soybean	Madbury, NH	950
Uchino et al., 2015	Soybean	Saporo, Japan	1100
Wells et al., 2016	Soybean	Salisbury, NC	980
Mennan et al., 2006	Collard	Samsun, Turkey	660
Ngouajio et al., 2003	Cucumber	Thermal, CA	100
Mennan et al., 2006	Lettuce	Samsun, Turkey	660
Ngouajio and Mennan, 2005	Lettuce	Lasing, MI	770
Campigilia et al., 2012	Pepper	Viterbo, Italy	755
Hutchinson and McGiffen, 2000	Pepper	Thermal, CA	100
Campigilia et al., 2010	Tomato	Viterbo, Italy	754
Masiunas et al., 1995	Tomato	Champaign, IL	950

† Collard, *Brasica olerecea* (Acephala Group); corn, *Zea mays* L.; cucumber, *Cucumis sativus* L.; lettuce, *Lactuca sativa* L.; pepper, *Capsicum annuum* L.; soybean, *Glycine max* (L.) Merr.; tomato, *Lycopersicon esculentum* L.