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Knowledge gaps in organic research: understanding interactions of cover crops and tillage for weed control and soil health

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Abstract Organic crop systems rely on tillage as the primary means to control weeds, but negative impacts of tillage may prevent farmers from achieving the potential soil health benefits of organic management. Cover crops have been suggested as a solution for overcoming this tillage trade-off directly by enhancing soil health and indirectly by providing weed control, thus reducing the need for tillage. In order to characterize the state of published research on the effects of cover crops on weed control and soil health in organic crop systems, we conducted a formal literature search on this topic and identified 116 relevant studies which were subsequently categorized by research focus, management strategy, and variables measured. We found 83 studies examined effects of cover crops on weed control and 33 studies examined effects of cover crops on soil health, but only 10 of the studies reported on both weed control and soil health effects. The lack of integrated studies examining both weed control and soil health responses to management highlights a research gap not sufficiently addressed by researchers, even though it is a topic of great interest to many organic farmers. A majority of studies (79) included reduced or no-till treatments, and annual grasses, clover, and vetch species were the most common cover crops. Assessments of aboveground biomass were the most common weed control measurements, while soil organic matter was the most common soil health measurement. Recommendations for future research needs include the following: more integrated assessments of the effects of cover crops on both soil health and weed control under varying tillage regimes; greater effort to characterize the soil health impacts of cover crop systems utilizing newly developed soil health indicators including soil physical parameters; long-term studies to assess dynamic soil health responses as well as perennial weed pressure (particularly in reduced and no-till organic systems); and greater allocation of research funding to regions outside of North America and Europe.

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Abbreviations

SOM	Soil organic matter
SOC	Soil organic carbon
CCORNT	Cover crop-based organic rotation no-till

Introduction

Tillage has traditionally been the primary method of weed control employed by organic farmers and plays an integral role in achieving the goals of high crop production and economic profitability. A broad array of tillage and cultivation implements has been designed to maximize weed control effectiveness under diverse conditions and cropping systems (Bowman 2002). However, the soil disturbance created by tillage is likely to cause an inherent trade-off with soil properties important for agroecosystem functioning (Smith et al. 2011). Reductions in tillage intensity in organic systems could ultimately mitigate these negative soil effects. However, organic reduced and no-till systems commonly result in problematic increases in weed pressure (Peigné et al. 2007; Mäder and Berner 2012; Carr et al. 2012; Armengot et al. 2015; Vincent-Caboud et al. 2017; Zikeli and Gruber 2017). Organic farmers recognize this limitation, citing the lack of a tillage option for weed control as the primary barrier to adoption of reduced tillage systems (Casagrande et al. 2015; Lowry and Brainard 2017). Balancing the contrasting positive and negative effects of tillage is an important ongoing challenge for organic farmers which is well illustrated by farmer surveys that rank "soil health" and "weed control" as their foremost management goals (Jenkins and Ory 2016; Zwickle et al. 2016). Thus, a central goal of organic research should be the development of management practices that mitigate the tillage trade-off by simultaneously providing weed control and improving soil health.

Soil health is a concept with growing popularity among both organic and conventional farmers and other stakeholders. Soil health is defined as the "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA NRCS). Soil health has been assessed using a broad suite of indicators that measure the physical, chemical, and biological properties of soil, and new indicators are still under development (Soil Health Institute 2020). A particular emphasis is often placed on properties that relate to soil biology, as these differentiate soil health from solely chemical and physical soil quality assessments. The concept of soil health is a component of organic farming, as exemplified by the USDA National Organic Program (NOP) guidelines, which state that producers must "select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion." In addition, one major driver of soil health, namely, soil organic matter (SOM), is specifically named in the NOP guidelines: "The producer must manage plant and animal materials to maintain or improve soil organic matter content."

Cover crops have been identified as a promising multifunctional strategy for enhancing weed control while simultaneously maintaining or enhancing soil functioning in organic systems (Fig. 1). A cover crop is a crop planted to occupy an otherwise empty niche in the cropping system. Cover crops are typically not harvested; rather, the biomass is left on the soil surface as residue or incorporated with tillage. The most common cover crop niche is as an off-season crop grown in the winter or summer gap between main crops, but cover crops can also be grown concurrently with the main crop when planted together (interseeded cover crops) or when established before the main crop (living mulches). Many species with diverse traits have been utilized as cover crops, so plant species can be mixed and matched to the niche and services required of the cover crop. Weed control services are best provided by species with high biomass and growth rates and allelopathic chemical production, while soil health services are best provided by species with high biomass production and low to moderate C:N ratios. Cover crops are explicitly encouraged by the NOP, which states that "the producer must implement a crop rotation including but not limited to sod, cover crops, green manure crops, and catch crops that provide the following functions that are applicable to the operation: (a) Maintain or improve soil organic matter content; (b) Provide for pest management in annual and perennial crops; (c) Manage deficient or excess plant nutrients; and (d) Provide erosion control."

The weed control service of cover crops is provided by various forms of competition (Osipitan et al. 2018; Verret et al. 2017). Actively growing cover crops fill empty ecological niches that could potentially be exploited by weeds, thereby providing competition with weeds for light, water, and nutrients. Additionally, cover crops can suppress weed seed germination and growth through production of allelopathic chemicals and/or suppressive mulch. Soil health benefits of cover crops are due to organic matter inputs as well as protection of the soil surface from erosion and temperature extremes. Cover crops increase the time period or area that growing plants occupy, and so accumulate additional biomass that is added to the soil system in the form of plant

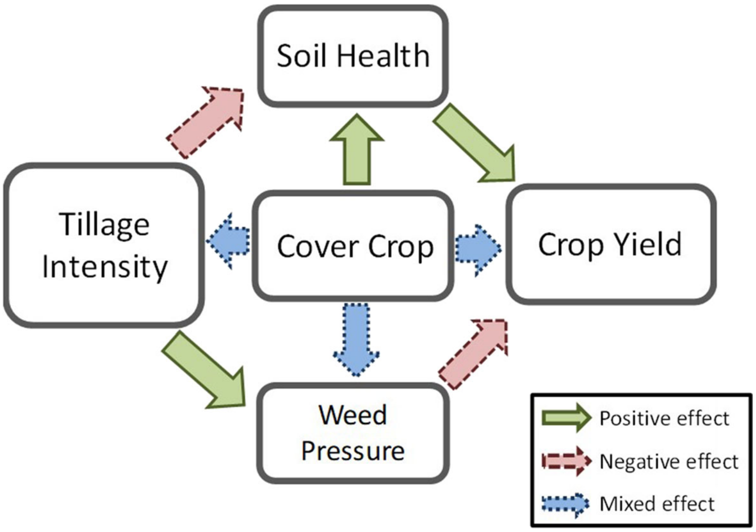

Fig. 1 Cover crops and tillage can have a direct influence on crop yield but also indirect effects through changes in soil health and weed pressure. Weed pressure and soil health are affected positively and negatively by tillage, respectively, but cover crops could play a role in mitigating the soil health trade-off. The direction and magnitude of cover crop effects on soil health, weed pressure, and crop yield will depend on the climate and edaphic characteristics, as well as management of the cover crop including termination method, cover crop species selection, and planting date and method. Solid green, dashed red, and dotted blue arrows indicate positive, negative, and mixed (both positive and negative) effects

root exudates as well as above- and below-ground biomass following termination. These biomass additions contribute to the accumulation of SOM, one of the primary drivers of soil health (Poeplau and Don 2015). Cover crops can promote soil biological activity and maintain a more diverse and structured soil food web by providing a continuous food source via root exudates and increased substrate complexity (Ferris et al. 2001). Protection of the soil surface by a growing or terminated cover crop can also improve soil health by preventing erosion of SOM-rich surface layers of soil (Daryanto et al. 2018). However, research reporting the effects of cover crops on soil health indicators other than total SOM from organic systems remains limited.

Termination of cover crops is an important management consideration that holds consequences for the tillage trade-off, as inversion tillage is the standard method for cover crop termination in organic systems due to its high termination efficacy. Tillage for cover crop termination also likely contributes to weed control similar to other, weed-focused tillage operations and can also accelerate SOM mineralization and consequently increase inorganic nutrient concentrations (Finney et al. 2015). However, increases in the intensity of tillage operations are likely to progressively offset the accrual of soil health benefits provided by cover crops. Alternative organic cover crop termination methods with limited or zero soil disturbance include roller-crimping, mowing, and winter kill of frost intolerant species. An organic cover crop-based system that may hold potential to minimize tillage operations, here called cover crop-based organic rotational no-till (CCORNT), utilizes low disturbance termination of a cover crop to generate a thick mulch that functions as the primary weed control tactic. This system has shown the most success when the subsequent main crop was soybean, but work with corn and various vegetable crops has also shown promise (Mirsky et al. 2010; Altieri et al. 2011; Silva 2014; Crowley et al. 2018). However, these reduced or no-till termination strategies often result in increased perennial weed pressure (Carr et al. 2012, 2013), further highlighting the trade-off between soil health and weed control that has persistently challenged organic farmers.

In addition to termination method, other management factors may influence the impact of cover crops on soil health and weed pressure. One of the most important is cover crop species, as species vary in growth habit, growth rate, soil fertility requirements, and cold and drought tolerance (Sarrantonio and Gallandt 2003). Cover crop species can be grouped by functional traits like high biomass production or N fixation capacity, and mixes of cover crops are often designed to incorporate multiple functional groups (Tribouillois et al. 2015; Blesh 2018; Ranaldo et al. 2019). Additionally, residue material from different cover crop species and different growth stages varies dramatically in chemical and physical characteristics which can influence the rate and fate of residue decomposition (Wagger et al. 1998).

Comprehensive searches of the scientific literature that characterize past research efforts can help identify research gaps and so inform future research efforts. A recent meta-analysis of organic research focused on the response of soil organic carbon (SOC) to tillage intensity (Cooper et al. 2016). Additionally, organic studies were included in broader examinations of the effects of agricultural practices, including tillage and cover crops, on soil health (Sandén et al. 2018), as well as the effects of cover crops on weed control (Verret et al. 2017; Osipitan et al. 2018; Osipitan et al. 2019). However, there remains a need for a comprehensive review of organic research focused on the integrative effects of cover crops and tillage on soil health and weed control.

To address this knowledge gap, we performed a systematic search of databases of published literature to assess the research effort that has focused on the role that cover crops can play in mitigating the potential trade-offs between soil health and tillage for weed control in organic cropping systems. The goals of this analysis were to (1) assess the current state of organic research on cover crop and tillage impacts on soil health and weed control and (2) identify the understudied aspects of organic cover crop systems that should be prioritized for future research.

Methods

Systematic literature search

A systematic search of the primary scientific literature was undertaken to identify peer-reviewed research publications with a focus on cover crops and soil health or weed control in organic systems. The search process identified studies that focused on organic tilled and/or no-till approaches to managing cover crops. The Web of Science, CAB Abstracts, and Agricola databases were queried on December 14, 2018, with the following search string:

("organic farm*" OR "organic agriculture*" OR "organic horticulture*") AND ("cover crop*" OR "catch crop*" OR "companion crop*" OR "green manur*" OR ley OR "liv* mulch") AND (weed* OR (Soil AND (health OR quality OR biolog* OR microb* OR chem* OR nutrient* OR physic* OR structur* OR Carbon OR C OR "organic matter")))

Additional relevant articles identified by the authors were also included. In total, 942 publications were collected and subjected to a review of the subject matter. Articles were removed from the database if they did not meet all of the following criteria:

1. Included at least one cover crop (as defined in Box 1) "treatment" as well as a "control" of no cover crop to assess the cover crop effect.
2. Treatment(s) and control both managed according to organic standards. Comparisons of a single organic treatment to conventional treatments were not included.
3. Measurements taken in a primarily annual arable field or horticultural crop system; studies from perennial systems (e.g., pastures, orchards, vineyards) were excluded as such systems frequently do not include tillage operations.
4. Weed control and/or soil health indicators were quantified. In this study, inorganic N (NO_3^- and/or NH_4^+) content was not considered an indicator of soil health.

Articles fulfilling the criteria were categorized as addressing the impacts on weed control and/or soil health. The scientific journal name, study year, and study locations were recorded. Publications were further categorized by the species of cover crop and cash crop investigated, cover crop niche, and tillage regime following the cover crop. Soil health indicators were broadly categorized by the soil parameter that was measured. The number of publications within a category was considered a proxy for research effort.

Results and discussion

Literature search results

A total of 116 publications satisfied the criteria for formal assessment of cover crop effects on weed control or soil health (Tables 1 and 2, Table S1). Ten publications reported both weed control and soil health effects of cover crops (Table 3), while soil health effects alone were reported in 23 publications, and weed control effects alone were reported in 83 publications. A majority (79) of the publications were published after 2010, with only four publications prior to 2000. Most studies (60) were conducted in North America, with 38 conducted in Europe and the remainder in Brazil, Japan, Turkey, and Iran. Maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), and soybean (*Glycine max* L.) were the most common main crops studied (28, 27, and 20 studies, respectively), while 41 publications studied various vegetable crops. In general, more than one cover crop species was examined in a given study (97 studies), and 60 included at least one mixture of two or more species. The winter cover crop niche was included in the majority (68) of the publications, summer cover crops included in 41 publications, and relatively few studies included interseeded cover crops and living mulches (28 and 12 studies, respectively).

Soil health-focused studies included a legume cover crop in most cases (27 studies), 21 included a grass cover crop, and 16 included a different plant functional group (Table 1). The most common tillage regime following the cover crop was full inversion tillage, but both no-till and reduced till strategies were also commonly utilized. The most common soil health indicator measured was SOM/SOC (15 studies), followed by assessments of nitrogen mineralization (11 studies) and microbial diversity and abundance (9 and 8 studies, respectively). Additional soil health indicators measured in the identified studies consisted of soil biological properties (C mineralization and enzyme activity) chemical properties (soil pH and labile fractions of organic matter), and physical properties (aggregate stability, bulk density, penetration resistance, and infiltration).

The cover crop species utilized in weed control-focused studies represented similar functional groups as soil health studies: 78 legumes, 65 grasses, and 35 other plant functional groups (Table 2). No-till was the most common soil management strategy following the cover crop, with 75 weed control-focused studies including no-till treatments, while inversion tillage was included in 63 studies and reduced till in 47 studies. Aboveground weed biomass was by far the most common weed assessment, reported in 76 studies. Weed seedbank and weed cover measurements were presented in 27 and 23 studies, respectively.

Cover crop effects on soil health and weed control

Cover crops are widely recognized as an important component of organic farming systems, potentially addressing the trade-offs caused by organic farming's continued dependence on tillage for weed control. Surveys have shown that cover crop adopters expect cover crops to contribute to improvements in soil health, as well as enhance weed control (O'Connell et al. 2015). However, direct assessments of the ability of cover crops to balance the dual goals of weed control and soil health are limited, as our comprehensive literature search identified only 10 studies that reported both weed control and soil health outcomes. These studies reporting both soil health and weed control outcomes, though sparse in number, suggest that significant challenges remain to optimize organic cover crop management to address the tillage trade-off (Table 3).

The degree of success in weed suppression or soil health improvement can be heavily influenced by the selection of the cover crop species. In Lithuania, an interseeded legume cover crop did increase total soil N relative to a grass cover crop, while the grass cover crop was more effective for weed suppression (Romaneckas et al. 2018). An initial report from Michigan suggests that mixtures of several species from different functional groups may be able to achieve these dual goals more effectively than individual species (Blesh 2018). Two years of several winter cover crop species did not impact the soil health indicators' water aggregate stability, penetration resistance, or SOC, although weed control was provided by a cover crop mixture that included a grass, legume, and brassica (Welch et al. 2016). Characterizing growth strategies and ecosystem services provided by various cover crops and mixtures has led to development and testing of frameworks to understand the ecological functions of cover crop species (Tribouillois et al. 2015; Finney and Kaye 2016). Such efforts can prove useful for advancing fundamental knowledge as well as provide practical guidelines for designing cover crop species mixes, and so deserve continued research attention. Elimination of tillage in the management of a cover crop does necessarily benefit all aspects of soil health or weed control, at least over a period of less than 2 years. Several experiments have shown mixed effectiveness of no-till management of cover crops for weed control in vegetable crops, possibly due to differences in the residue production of the different cover species tested (Lounsbury and Weil 2015; Finney et al. 2009; Bulan et al. 2015). Each of these studies noted negative effects of no-till compared with conventional tillage management of cover crops on soil physical properties, particularly soil bulk density and porosity. Conversely, several soil health indicators (C mineralization, N

Table 1 Key properties of studies that have examined the effects of cover crops on soil health

Soil health publications (33 total)*

Journal name**	Year	Location	Main crop species	Cover crop species†	Cover crop niche	Post-CC tillage	Measurement
Applied Soil Ecol (3)	Prior to 2000 (0)	N America (15)	Maize (10)	Vetch sp. (16)	Winter (20)	Inversion tillage (24)	Soil organic matter/carbon (15)
25 others (30)	2000–2005 (1)	Europe (12)	Wheat (8)	Clover sp. (14)	Spring/summer (9)	Reduced till (10)	N mineralization (11)
	2006–2010 (7)	Brazil (3)	Soybean (7)	Other legume (11)	Interseeded (8)	No-till (14)	Microbial diversity (9)
	2011–2015 (14)	Japan (2)	Root crop (7)	Cereal rye (12)	Living mulch (2)		Microbial abundance (8)
	2016–2019 (10)		Other cereal (4)	Ryegrass sp. (5)			Soil pH (7)
			Pulse/oilseed (4)	Other grass (9)			Soil bulk density, penetration resistance, or infiltration (8)
			Veg. Tomato (4)	Brassica (19)			C mineralization (6)
			Veg. Brassica (4)	Buckwheat (4)			Soil enzyme activity (6)
			Veg. Other (4)	Other (6)			Labile soil organic matter fractions (3)
			Not specified (3)				Aggregate stability (4)

*10 publications present both weed control and soil health impacts of cover crops

**Only journals with more than 2 publications are individually listed

† 18 pubs included mixtures

The number of publications in each category is indicated within "()"

Table 2 Key properties of studies that have examined the effects of cover crops on weed control

Weed control publications (93 total)*

Journal name**	Year	Location	Main crop species	Cover crop species[††]	Cover crop niche	Post-CC tillage	Measurement
Agron J (11)	Prior to 2000 (4)	N America (51)	Wheat (21)	Cereal rye (39)	Winter (53)	Inversion tillage (63)	Weed biomass (76)
Renew Food Ag Syst (11)	2000–2005 (9)	Europe (29)	Maize (19)	Oat (16)	Spring/summer (35)	Reduced till (47)	Weed seedbank (27)
Euro J Agon (7)	2006–2010 (20)	W Asia (6)	Soybean (15)	Ryegrass sp. (16)	Interseeded (22)	No-till (75)	Weed cover (23)
Crop Protection (6)	2011–2015 (30)	Brazil (4)	Other cereal (13)	Barley (11)	Living mulch (11)	Unclear (6)	
Weed Sci (6)	2016–2019 (30)	Japan (3)	Pulse/oilseed (13)	Wheat (8)			
Weed Tech (6)			Root crop (11)	Other grass (15)			
Weed Res (5)			Forage (4)	Clover sp. (39)			
Ag Ecosys Env (4)			Veg. Brassica (9)	Vetch sp. (35)			
Biol Ag Hort (4)			Veg. Cucurbit (7)	Pea (18)			
Field Crops Res (4)			Veg. Tomato (6)	Medicago sp. (14)			
HortSci (4)			Veg. Pepper (6)	Other legume (23)			
21 Others (25)			Veg. Lettuce (5)	Brassica (24)			
			Veg. Other (6)	Buckwheat (11)			
			Not specified (6)	Other (8)			

*10 publications present both weed control and soil health impacts of cover crops

**Only journals with more than 2 publications are individually listed

[††] 47 pubs included mixtures

The number of publications in each category is indicated within "()"

Table 3 Summary of articles addressing both weed control and soil health effects of cover crops in organic systems

Study	Location	Main crops†	Cover crops†	CC niche	CC tillage regimes*	Fallow weed control	CC weed effects**	CC soil health effects**
Anugroho et al. 2009	Japan	None	Hairy vetch	Winter	IT	No weed control	↓ weed biomass	↑ phosphate availability
Baldivieso-Freitas et al. 2018	Spain	Spelt; chickpea; winter wheat; lentil	Oat; white mustard; bitter vetch; common vetch††	Winter	IT, RT	Tillage	↑ weed biomass	NS
Bulan et al. 2015	Wisconsin	Cabbage	Buckwheat; Tartary buckwheat	Spring/summer	IT, NT	Tillage	↓ weed biomass	↑ penetration resistance
Crowley et al. 2018	New York	Soybean	Cereal rye	Winter	IT, NT	Tillage	↑ weed biomass	↑ C min, N min, infiltration
Finney et al. 2009	North Caroli-na	Cabbage	Sorghum-sudangrass	Spring/summer	IT, NT	Tillage; mulched w/ straw	↑ weed biomass compared to mulch control	NS
Germeier 2006	Germany	Winter wheat; cereal rye	Yarrow; cornflower; chamomile; dandelion; white clover	Living mulch	IT	Tillage	↓ weed biomass	NS
Lounsbury and Weil 2015	Maryland	Spinach	Forage radish; oat††	Winter	IT, NT	Tillage; hand weeded	↓ weed cover	↓ porosity
Romaneckas et al. 2018	Lithuania	Sugar beet	Persian clover; white mustard; spring barley	Interseeded	IT, NT	Tillage; Mowed	↓ weed biomass compared to mowed	↑ total N compared to mowed
Wang et al. 2008	Florida	Turnip; lima bean	Sunn hemp; cowpea	Spring/summer	IT	Tillage	Mulch ↓ broadleaf numbers	Mulch ↓ parasitic nematodes, ↑ predatory nematodes
Welch et al. 2016	Illinois	Soybean; corn	Forage radish; buckwheat; hairy vetch; cereal rye††	Winter	IT	Tillage	↓ weed biomass	NS

† Bitter vetch (*Vicia ervilia* L.), buckwheat (*Fagopyrum esculentum* Moench), cabbage (*Brassica oleracea* L.), cereal rye (*Secale cereale* L.), chamomile (*Matricaria recutita* L.), chickpea (*Cicer arietinum* L.), common vetch (*Vicia sativa* L.), cornflower (*Centaurea cyanus* L.), cowpea (*Vigna unguiculata* L.), dandelion (*Taraxacum officinale* F.H. Wigg.), forage radish (*Raphanus sativus* L.), hairy vetch (*Vicia villosa* Roth), lentil (*Lens culinaris* Medikus), lima bean (*Phaseolus lunatus* L.), oat (*Avena sativa* L.), Persian clover (*Trifolium resupinatum* L.), sorghum sudangrass (*Sorghum bicolor* (L.) Moench x *Sorghum sudanense* (Piper) Staph.), soybean (*Glycine max* L.), spelt (*Triticum spelta* L.), spinach (*Spinacia oleracea* L.), spring barley (*Hordeum vulgare* L.), sugar beet (*Beta vulgaris* L.), Sunn hemp (*Crotalaria juncea* L.), Tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertn.), turnip (*Brassica rapa* L.), winter wheat (*Triticum aestivum* L.), white clover (*Trifolium repens* L.), white mustard (*Sinapis alba* L.), yarrow (*Achillea millefolium* L.)

†† At least one mixture of the listed species was also examined

**IT* intensive tillage, *RT* reduced tillage, *NT* no tillage

**Statistically significant effects were not necessarily observed in all CC treatments; *NS* no significant effects mineralization, and infiltration) were improved by a roller-crimped no-till winter cover crop, yet weed biomass was also greater (Crowley et al. 2018). However, permanganate oxidizable C (POXC) and aggregate stability were not affected, while weed biomass was an order of magnitude greater than the tilled no cover crop control.

Several studies suggested that overcoming trade-offs between weed control and soil health may be possible with cover crops. One study found that a legume cover crop improved soil phosphate availability following incorporation and also suppressed weed biomass prior to incorporation by tillage (Anugroho et al. 2009). Another study employed a unique management technique that consisted of temporary harvest of the aboveground growth of a legume cover crop, followed by tillage and then mulching of the field with the harvested plant material (Wang et al. 2008). Broadleaf weed numbers were suppressed, and soil health was enhanced by the cover crop mulch, as indicated by increased abundance of beneficial nematodes and suppression of harmful nematodes. While the practicality of implementation of this technique may be a challenge for its widespread adoption, it does highlight the potential for innovative systems that combine cover crop residue retention with tillage opportunities to overcome the trade-off between weed control and soil health.

Management of soil moisture and nutrient dynamics remains a challenge in organic cover crop systems, as producing sufficient cover crop biomass to reduce weed pressure requires significant soil moisture and also immobilizes significant quantities of nutrients such as N and P which may remain unavailable to the subsequent crop. A 4-year study from Spain showed that dry growing conditions limited the growth of a mixture of several species of cover crops, and as a result the cover crop did not improve soil health indicators and also resulted in increased weed pressure in a subsequent crop when a reduced tillage system was implemented (Baldivieso-Freitas et al. 2018). In Germany, while several species of living mulch cover crops did not influence soil pH and total SOM, they did provide weed control services to cereal crops (Germeier 2006). However, main crop yield was negatively impacted by the cover crop apparently due to nutrient (especially N) competition. Overall there is a need for additional studies that simultaneously examine both the weed control and soil health implications of cover crop management in diverse environmental contexts, particularly over periods longer than two growing seasons. Such integrative research is required to develop cover crop best management practices that achieve the dual goals of improved soil health and weed control.

Soil health effects of cover crops

A relatively small number of publications reported soil health effects of cover crops, despite soil health improvement being the primary motivation for many organic cover crop adopters (Casagrande et al. 2015). The most commonly observed indicator reported in the identified publications was SOM/SOC. Soil organic matter should continue to be reported in soil health focused research as it is a primary driver of soil biological, chemical, and physical processes (Lehman et al. 2015). However, SOM changes can be difficult to measure due to the slow-changing nature of SOM and the inherent variability within experimental sites. Soil properties that are more sensitive to management changes can indicate the direction of soil health changes more quickly and could be useful for the short-term research common in agricultural systems. Indicators of labile SOM fractions and biological processes, for example, POXC, soil protein, and soil respiration (C mineralization), are relatively inexpensive to measure and may be more sensitive to management and so could be easy to implement more widely (Morrow et al. 2016; Hurisso et al. 2018a, b).

Biological soil health indicators are relatively new, yet research has already demonstrated that cover crop management can influence microbial community size, composition, and activity (Wortman et al. 2013; Liang et al. 2014; Tiemann et al. 2015; Brennan and Acosta-Martinez 2017). Several other studies have focused on nematode communities, with cover crops showing mixed effects on nematodes (Wang et al. 2008; Dupont et al. 2009; Ito et al. 2015). Tying microbial effects to changes in ecosystem function is an important area of active research, with recent work indicating that mycorrhizal fungi or soil bacterial communities are important for mediating cover crop effects on ecosystem function such as nutrient cycling, crop productivity, and weed suppression (Njeru et al. 2014, Fernandez et al. 2016, Trinchera et al. 2019).

Indicators of soil physical condition such as aggregate stability and penetration resistance can provide insights into components of soil health such as water infiltration and soil aeration (Topp et al. 1997). Physical soil health indicators were also reported by only a small number of studies, although cover crops are known to significantly affect soil structure in conventional agricultural systems (Blanco-Cacqui et al. 2015). Opportunities clearly exist to utilize biological and physical soil health indicators to further assess soil health responses to cover crops.

While many of the soil health indicators suggested above can be more sensitive to change than total SOM, they can still take several years to develop observable differences in response to management strategies like tillage and cover crops. Therefore, a greater emphasis on long-term (> 5 years) studies of organic systems will be necessary to fully examine the effects of cover crops and tillage on soil health.

Weed control effects of cover crops

A robust amount of literature focused on weed control effects of cover crops, likely due in part to the straightforward nature of aboveground plant biomass measurements, the primary measurement used for weed control research. Cover crops can play an important role in addressing the weed control challenge for organic systems, but cover crop management decisions such as species selection, seeding rate, and establishment/termination method and timing will be critical to successful deployment of cover crops for weed control and require greater research attention (Osipitan et al. 2019). The utility of cover crop species mixtures for weed control remains an active area of research, with some research indicating that monocultures provide similar weed control as mixtures (Holmes et al. 2017). Development of more mechanistic frameworks for understanding the ecological niches and traits of cover crop species may enable the design of functionally diverse species mixtures that can ensure weed control services better than single species monocultures (Ranaldo et al. 2019). Relatively few studies in our literature search followed changes in weed pressure due to cover cropping over more than 2 years (data not shown), yet both annual and perennial weed populations can take several years to respond to management (Hiltbrunner et al. 2008; Orloff et al. 2018). Thus, increasing long-term research efforts focused on alternative weed control strategies that include cover crops will be valuable for advancing organic weed control research. Additionally, opportunities exist to focus future research on integrating cover crops into more aggressive and proactive, long-term management strategies (e.g., stale seedbeds, weed-free fallow) that seek to deplete the weed seedbank to prevent weed pressure rather than manage the weed population at a moderate level (Gallandt 2006).

Reduced and no-till cover crop systems

A number of studies examined the weed control or soil health aspects of reduced and no-till systems, with several showing that organic reduced tillage systems can result in increased weed pressure over time (e.g., Ngouaijio et al. 2003; Delate et al. 2012; Carr et al. 2013). Studies specifically investigating the CCORNT system suggested that improved management of a cover crop to optimize biomass production as well as periodic, targeted use of high residue cultivation may be able to limit weed control issues (Reberg-Horton et al. 2012; Mirsky et al. 2013; Bavougian et al. 2019; Beach et al. 2018). Initial soil health results from one study suggest that CCORNT holds potential to enhance soil health (e.g., Crowley et al. 2018) but the soil health benefits of this system remain largely undocumented and require testing in additional environments and cropping systems. Continued development and refinement of CCORNT is warranted as it may be one of the best techniques for maximizing the benefits of cover crops while minimizing the negative impacts of tillage (Schoenbock et al. 2017).

Study locations

The vast majority of the identified studies were conducted in North America and Europe, yet the tillage trade-off is not restricted to these regions. Indeed, soil degradation due to agriculture is a particular challenge in many less-developed regions such as sub-Saharan Africa, where organic farming knowledge could prove especially beneficial to traditional low-input agriculture (Te Pas and Rees 2014; Tully et al. 2015; Jouzi et al. 2017). Thus, the potential impact of new cover crop research to overcome the tillage trade-off will be particularly high in these regions. Indigenous knowledge and practices should inform the design of research trials, and an emphasis should be placed on publishing research results in peer-reviewed journals to increase the visibility of this research.

Summary and recommendations

The reliance of organic systems on tillage for weed control compromises improvements in soil health, an explicit goal of most organic farmers. Cover crops are a main avenue for addressing this challenge, and a literature search identified 116 peer-reviewed publications relevant to understanding how cover crops can address the weed control-soil health trade-off. However, only 10 publications reported both soil health and weed control outcomes. Much progress has been made in understanding how cover crops influence weed control, including under reduced till or no-till systems, but opportunities exist to further advance organic weed control research. Soil health-focused research is more limited and primarily reported SOM/SOC and soil C and N mineralization results, with fewer studies investigating soil physical properties. We recommend additional resources be directed to understanding how cover crops can be most effectively deployed to enhance both weed control and soil health and thus address the tillage trade-off. Such research will be vital for uncovering paths toward more sustainable, productive, and profitable organic systems. Based on our formal survey of the literature, specific recommendations for future organic cover crop research include the following:

1. Integrated research that simultaneously assesses the effects of cover crops on both soil health responses and weed control services under varied tillage regimes. Studies should aim to explore potential trade-offs between soil health and weed control.
2. Investigate soil health impacts of cover crop systems, including cover crop-based organic no-till systems, utilizing recently developed soil health indicators including soil physical parameters that may be more sensitive to rapid management changes than SOM. Furthermore, establishing how the changes in soil health indicators relate to changes in agroecosystem function remains a research priority.
3. Increase the duration of studies to improve the likelihood of measuring soil health responses and long-term shifts in weed communities. On-farm research comparing well-established cover crop systems could also provide insight into long-term effects on soil health and weed control.
4. Weed control studies should explicitly consider long-term implications of cover crops on both perennial and annual weed pressure, particularly in reduced and no-till systems such as CCORNT. Initial findings show such systems that hold potential to overcome the tillage trade-off between weed control and soil health, but developing techniques for consistent perennial weed control will be important for long-term viability.
5. Greater allocation of research funding to regions outside of North America and Europe, and particularly in less-developed countries. Integrating technologies like cover crops and reduced tillage techniques into traditional cropping systems hold potential for improving environmental and socio-economic outcomes for small-holders.

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