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Review

Impacts of Organic Zero Tillage Systems on Crops, Weeds, and Soil Quality

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Abstract: Organic farming has been identified as promoting soil quality even though tillage is used for weed suppression. Adopting zero tillage and other conservation tillage practices can enhance soil quality in cropping systems where synthetic agri-chemicals are relied on for crop nutrition and weed control. Attempts have been made to eliminate tillage completely when growing several field crops organically. Vegetative mulch produced by killed cover crops in organic zero tillage systems can suppress annual weeds, but large amounts are needed for adequate early season weed control. Established perennial weeds are not controlled by cover crop mulch. Integrated weed management strategies that include other cultural as well as biological and mechanical controls have potential and need to be incorporated into organic zero tillage research efforts. Market crop performance in organic zero tillage systems has been mixed because of weed, nutrient cycling, and other problems that still must be solved. Soil quality benefits have been demonstrated in comparisons between organic conservation tillage and inversion tillage systems, but studies that include zero tillage treatments are lacking. Research is needed which identifies agronomic strategies for optimum market crop performance, acceptable levels of weed suppression, and soil quality benefits following adoption of organic zero tillage.

Keywords: organic farming; biological farming; ecological agriculture; conservation tillage; no-till; cover crops; soil quality; weeds

1. Introduction

Proponents of organic farming argue that soil quality is best promoted in food production systems where biological, cultural, and physical practices are relied on to supply crops with adequate nutrition and suppression of pests. Some have argued that use of synthetic fertilizer and pesticides is unnecessary for maintaining a sufficient supply of nutritious food to feed a growing global population [1] and, worse yet, may lead to practices that degrade the environment in general, and soil quality in particular [2]. Others maintain that crop yield estimates following large-scale adoption of organic farming methods are unrealistic [3], and conventional farming systems which include the regular use of synthetic fertilizer and pesticides are the best option for providing an adequate global food supply while maintaining and even enhancing soil quality [4,5]. Recent published meta-analyses (e.g., [6]) suggest that widespread replacement of conventional with organic farming is not recommended if substantial increases in food production are needed to feed a population of 10 billion humans by 2050, as some have projected [7]. Seufert *et al.* [8] and others [6] reported an average yield drag of 20% when crops were grown using organic compared with conventional methods. Still, Reganold [9] argued that organic farming has a place in supplying a sufficient and nutritious food supply in the future, pointing out that high yields can be produced by organic farmers. In addition, organic farming may be a better strategy for promoting the environmental and socio-economic sustainability of agrarian life than conventional farming [9].

In a sense, all farming was *de facto* organic prior to the development and use of synthetic fertilizer and pesticides, beginning in the 1940s. Advances in plant genetics, farm equipment and other scientific and technological improvements suggest that modern organic farming is a vast improvement over earlier versions. Still, many of the principles underlying farming practices prior to the 1940s continue to guide organic farmers today. For example, Anderson [10] pointed out the value of diverse crop rotations for weed suppression to modern organic farmers, while others [11] indicated the benefits of well-designed rotations in the cycling of nutrients for the crops being grown. Sir Albert Howard and Lady Eve Balfour, two important figures in the organic farming movement, likewise emphasized the value of crop rotation when farming organically back in the 1940s [12]. Howard and other pioneers of the modern organic farming era, which began in the 20th century [13], also extolled the value of recycled organic wastes as important soil amendments. While certain beliefs held by some of these early leaders of modern organic farming seem questionable today, their appreciation for soil biology and the importance of soil quality in affecting crop performance was argued as being ahead of its time [13].

There is debate regarding the relative merits of adopting organic farming methods rather than conventional zero tillage (ZT) practices on soil quality. Trewavas [5] argued strongly in favor of conventional ZT, pointing out that the tillage relied on for weed control by organic farmers can lead to degradation of soil structure and reduction in soil (C) content at the surface, as well as declines in soil macro-organisms. Certainly there is evidence suggesting that conventional ZT has advantages compared with conventional tilled systems in regards to soil aggregation and other aspects of soil quality [14]. However, side-by-side comparisons between conventional ZT and tilled organic farming systems have failed to reveal a distinct advantage to conventional ZT [15,16]. These field studies were confounded by management differences between the conventional ZT and tilled organic systems—regular additions of animal manure and/or green manures were included only in the organic systems while synthetic fertilizers were used in the conventional systems—making it impossible to separate the soil quality impacts due to management system (*i.e.*, conventional and organic) from cultural practice (e.g., presence or absence of manure and/or cover crops). Results of these studies failed to quell interest among organic farmers in the development of conservation tillage systems for use on organic farms [17].

2. Organic Conservation Tillage

Improvements in crop performance and soil quality can result following conversion from clean or conventional tillage to conservation tillage systems, defined broadly as any set of practices that reduce soil or water loss compared with a conventional system based on soil inversion [18]. Minimum tillage and reduced tillage are often used interchangeably with conservation tillage in this broad context. More narrowly, conservation tillage is defined as any set of practices that leaves at least 30% of the soil surface covered by crop residue after seeding [18]. Zero tillage, also referred to as no tillage, direct seeding and direct drilling, includes those cropping systems where soil disturbance is limited to what occurs when seeding using disk openers sometimes preceded with narrow cutting coulters mounted onto the planting unit. Zero tillage is the conservation tillage system which retains the greatest amounts of crop residue on the soil surface, and the benefits are most pronounced in dry regions following adoption of ZT where the soil water conservation that occurs is a particular advantage [19]. Recognizing this, Peigné *et al.* [20] argued that adoption of ZT and other conservation tillage practices should enhance microbial activity and C sequestration, reduce nutrient leaching and erosion, and lower fuel use on organic farms. They pointed out several cultural practices that could be adopted during and following conversion to conservation tillage systems for weed control, but acknowledged that achieving an adequate level of suppression over the long term could be a challenge. Soil compaction and nutrient deficiency problems also might develop following adoption of conservation tillage practices on organic farms. These researchers suggested a “staged approach” whereby soil and climate best suited to conservation tillage first was identified, followed by careful planning of crop rotations to maximize opportunities for nutrient cycling and weed suppression, as has been detailed by others [10]. Cover crops likely would be an important component in at least some of these crop rotations, possibly as weed-suppressive mulch.

European researchers replaced inversion practices with less aggressive methods and decreased the depth of soil disturbance in their efforts to reduce the amount of tillage on organic farms [21]. For the most part, they generally have not considered the complete elimination of tillage when growing annual market crops organically [22], although there have been exceptions [23]. There are potential benefits which can result from ZT which may not occur in systems with even limited amounts of soil tillage [19]. For this reason, organic farming researchers in North America have focused on eliminating tillage completely when growing annual crops during selected crop phases and reducing tillage during other crop phases across a rotation.

2.1. Organic Zero Tillage

Cover crops are an integral component of organic ZT systems. Cover crops offer several ecosystem services when incorporated into rotations with market crops, including soil and water quality improvements [24] and nutrient cycling advantages [24,25]. However, the primary use of cover crops in organic ZT is to create vegetative mulch for weed suppression. As little as 2,700 kg ha^{-1} of above-ground dry matter produced by fall-seeded cover crops can suppress annual weed density the following spring and early summer by as much as 75% [26], although at least 7,000 kg ha^{-1} of residue may be needed to suppress annual broadleaf weeds by 80% [27]. Teasdale [26] concluded that cover crop residue could provide good early season weed suppression but that full-season weed control was not provided. Likewise, cover crop residue was unable to suppress growth of well-established perennial weed species.

An early challenge in the development of organic ZT was devising methods for killing cover crops that involved little if any soil disturbance. Rollers received the greatest attention. Creamer *et al.* [28] reported better results when cover crops were killed using a roller compared with a flail mower, but a blade plow was attached to the roller and shallow soil disturbance occurred. Ashford and Reeves [29] were perhaps the first North American researchers to consider terminating cover crops mechanically but without tillage using a roller-crimper, borrowing an idea first developed and used in South America following the introduction of conventional ZT. A roller-crimper essentially is a rolling drum with blades of various designs attached to it. The blades are dull and used to crush rather than cut the cover crops. Roller-crimpers had been developed and used in South America following the introduction of conventional ZT. The two researchers concluded that small-grain cover crops could be killed effectively if rolling-crimping was delayed until advanced growth stages (Zadoks growth stage, ZGS 85; [30]). Recent roller-crimper designs have improved efficacy of killing cover crops and enhanced operator comfort when used in the field [31–33]. Current models can kill over 90% of a rye cover crop when terminated as early as 50% anthesis or ZGS 65 in some environments [34].

Various market crops have been seeded directly into cover crop mulch killed using a roller. One of the earliest published reports focused on seeding cotton (*Gossypium hirsutum* L.) directly into a rye (*Secale cereale* L.)/hairy vetch (*Vicia villosa* Roth) vegetative mulch after the cover crop mixture was killed by rolling and also flailing [35]. Interest in organic ZT grew as reports emerged that field crops, notably maize (*Zea mays* L.) and soybean (*Glycine max* L.), could be grown successfully without tillage when seeded into killed hairy vetch and rye cover crop mulch [36]. The enthusiasm generated among organic farmers spurred a growing number of researchers across North America to investigate organic ZT as an emerging cropping strategy. Results of several studies were summarized in a special issue on organic conservation tillage in *Renewable Agriculture and Food Systems* in 2012 [33,37–41].

Research in the southeastern USA demonstrated excellent dry matter production potential of rye cover crop (≥9,000 kg ha^{-1}), with the caveat that little information existed on how inclusion of organic ZT crop phases impacts weed community shifts over the long-term [35]. Similar concerns were echoed by Mirsky *et al.* [37] in their summary of organic ZT in northeastern USA, along with concurrence of an earlier suggestion that the vegetative mulch produced cover crops, regardless of amount, probably would not suppress established perennial weeds [26]. Cover crop mulch did suppress weeds in both the north central USA [40] and southwestern Canada [41], with dry matter production potential of selected cover crop treatments in some environments equaling and even surpassing those reported in the southeastern USA. Depletion of soil water and delays needed to ensure cover crops were killed by rolling-crimping were particular concerns when attempting to follow killed cover crops with market crops in cool dry regions [40].

Recent performance of market crops in organic ZT systems has been mixed. Grain yield of maize and soybean seeded directly into rolled-crimped cover crop mulch was greater than average yields of conventional farmers in several instances in the northeastern USA [37]. In contrast, yields of both crops were reduced by over 50% in some environments in the U.S. Corn Belt [39]. Among horticultural crops, irrigated tomato (*Lycopersicon esculentum* Mill.) yields were maintained in an organic ZT system compared with a tilled organic system in the Midwest region [39], while attempts to produce tomato and eggplant (*Solanum melongena* L.) in organic ZT systems were complete crop failures in western USA [38]. Competition from weeds, cover crop regrowth, and nutrient availability concerns were suggested as reasons explaining the poor performance of market crops in organic ZT systems in these regions [37,39], along with soil water depletion and market crop seeding delays as were identified by others [40].

2.2. Current Agronomic Challenges to Commercial Adoption of Organic Zero Tillage

The reliance of vegetative mulch for weed suppression in organic ZT requires cover crop kill to be consistent and effective. Recent research suggested that cover crop mulch may be most persistent when a roller-crimper is used compared with other ZT termination methods like mowing [42], and that small-grain [34] and legume [40–42] cover crops can be killed effectively by rolling-crimping. However, cover crops must reach reproductive growth stages to be killed effectively, and this typically results in seeding maize and soybean three or more weeks after the latest recommended seeding date [43,44]. Yield potential of the market crop typically is reduced and harvestable yield may be prevented completely when seeding is delayed several weeks beyond the last recommended seeding date, particularly at upper latitude regions with short growing seasons.

A small percentage of cover crop plants generally are not killed (<10%) even though rolling-crimping is considered an effective termination method [34,42]. The plants that survive compete for water and nutrients with the market crops seeded after rolling-crimping the cover crop [45]. Competition from a small percentage of cover crop plants may be a minor nuisance in sub-humid and humid environments in fields where soil fertility levels are high, but they pose a significant obstacle to successful production of market crops in regions with limited rainfall and/or low soil fertility levels because of their competition for growth resources [38,40]. Killing efficiency improves as rolling-crimping is delayed and can reach levels of 95% or more, but increases the chances that viable seed is produced by cover crops before being killed. Volunteer seedlings can result from any viable seed produced by cover crops and can compete with subsequent crops for nutrients, sunlight and water.

Plant-available nitrogen (N) is taken up by cover crops during growth, and its availability to subsequent market crops is a function of the C:N ratio along with amounts of cellulose, hemicellulose, and other tissue constituents once cover crop plants are killed, and the soil microbial community [46]. Reberg-Horton *et al.* [46] speculated that rolled-crimped hairy vetch and other legume cover crops with small C:N ratios may enhance the soil N pool with little or no delay following termination, although N deficiency symptoms were observed in maize seeded following a rolled-crimped hairy vetch cover crop [39]. Soil N probably will be immobilized for several weeks when rolling-crimping rye and other cover crops with large C:N ratios, but this could give legumes and other low N-demand crops may be at a competitive advantage when directly seeded into the cover crop mulch relative to certain weeds which have high N-demands in these environments [46]. A much better understanding of soil nutrient cycling is needed in organic ZT systems so that appropriate strategies can be developed which optimize uptake of N and other nutrients by market crops.

Organic ZT as conceived by Moyer [36] and others (e.g., [35]) involves production of a summer-seeded market crop after killing a fall-seeded cover crop in a single growing season. Fast-growing, winter hardy, early maturing cover crop germplasm is needed in this system so that subsequent market crops can be seeded within the recommended planting period. An alternative is to roll-crimp the cover crop during one growing season and then produce a market crop the next growing season, thereby eliminating the need to delay market crop establishment so cover crops can be killed effectively in the same year. This mirrors a common practice on many organic farms in arid regions where cover crops are tilled under as green manures during the first year and then followed the second year with a market crop [47]. Late-maturing cover crop cultivars capable of producing large amounts of dry matter would be preferred over early maturing cultivars in this two-year system. Full-season weed suppression could not be provided in the second year by a cover crop killed during the first year, but only three to six weeks may be needed until market crop plants are established and able to compete successfully with weed seedlings just emerging through the decomposing cover crop residue. Such a system has been considered in Canada where spring wheat (*Triticum aestivum* L. emend. Thell.) was grown the year after rolling-crimping a cover crop mixture of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.) [48].

Organic ZT presently is used to denote systems where soil is left undisturbed during certain crop phases which are rotated with other crop phases where some tillage is done [36]. This “rotational tillage” scheme has been used in some conservation tillage systems managed conventionally to combat the dual problems of soil erosion (ZT crop phases) and subsoil compaction (tilled crop phases) [49]. The primary use of tilled crop phases in organic ZT is to suppress weeds not controlled during ZT crop phases by cover crop mulch. Animal grazing has been used for weed suppression in various cropping systems [50,51] and might be substituted for tilled crop phases in organic ZT farming systems for the same purpose. Appropriate integration of livestock grazing also could be used to synchronize the release of plant-available nutrients in animal excrement and when they are needed by cover and market crops.

3. Weed Management

3.1. Organic Zero Tillage Effects on Weeds

Weed management represents a major challenge to adopting conservation tillage in organic systems [52,53]. Tillage influences weed life cycle processes by directly destroying seedlings, redistributing seeds vertically in the soil profile, and altering soil properties that influence seed persistence, dormancy, germination, and seedling survival [20,54]. Therefore, shifts in weed community population dynamics frequently occur when any type of conservation tillage is adopted [55,56], including ZT. Understanding tillage effects on weed community dynamics can be challenging because the effects are variable and depend on interactions with other management tactics, environmental conditions, and weed biology [57–59]. Most research on ZT effects on weeds has been conducted in conventional systems were synthetic herbicides are used since organic ZT approaches are relatively new [23,40,41]. Research regarding the effects of ZT on weeds in conventional systems might be used to anticipate consequences of ZT in organic systems for processes such as weed seed distribution within the soil profile. However, other observations from ZT studies that include herbicide applications may need reconsideration when applied to organic systems since herbicide use is such a strong filter on weed community assembly processes [59–61]. Likewise, research results from conventional *vs.* organic tillage studies oftentimes will differ because organic fields tend to have greater weed species density and diversity than fields managed conventionally [6,62–65].

Research in organic systems that compare less aggressive tillage to standard practices has been conducted more extensively and longer than research where tillage is eliminated completely (*i.e.*, organic ZT). Many of these studies have compared inversion (moldboard plowing) to alternative lower-impact tillage practices such as chisel or disk cultivation. Results from these studies generally demonstrated that conservation tillage is associated with increased weed pressure [39,52,53]. The enhancement in weed pressure primarily results because inversion tillage tends to distribute weed seeds to a depth from which emergence is unlikely, while non-inversion tillage leaves many weed seeds in the upper soil horizon which enhances the likelihood of emergence [10,53,66]. However, research results have been somewhat variable because of differences in crop management (e.g., crop selection). For example, Vakali *et al.* [67] found that conservation tillage in an organic system decreased crop growth because of increased weed pressure in barley (*Hordeum vulgare* L.) but not in rye because of tillage timing differences between these two crops.

Changes in tillage systems frequently result in weed species shifts as well as changes in density. Adoption of conservation tillage in an organic system resulted in increased annual weed cover in a three-year rotation of wheat, spelt, and sunflower (*Helianthus annuus* L.) [68]. There were differences in dominant weed species associated with each crop but weed pressure reduced crop yield only for wheat and spelt. Increased surface litter provides an ideal microclimate for the germination and survival of winter annuals, and conservation tillage has been associated with a proliferation of winter annual weeds [57]. Additionally, downy brome (*Bromus tectorum* L.) and some winter annuals emerge easily from the soil surface and thus benefit from tillage reductions when conservation tillage systems are employed. Conservation tillage also favors the spread of perennial weeds [69,70]. Previous research has demonstrated increases in winter annual weed species in organic systems [60], and increases in troublesome perennial species such as dandelion (*Taraxacum officinale* Weber) and Canada thistle (*Cirsium arvense* L.) in organic conservation tillage systems [53,68]. For these reasons, organic ZT systems may be particularly prone to winter annual and perennial weed problems.

Few studies have evaluated the impact of organic ZT systems specifically on weed populations. A study conducted in Quebec, Canada, resulted in a total crop failure in maize under organic ZT management and a 50% reduction in soybean yield compared to moldboard plowed plots [71]. These somewhat extreme results may be explained by several factors. The research was conducted in 20-year-old ZT plots that contained 50% to 80% more weed seeds than in chisel or moldboard plowed plots, highlighting the importance of considering field history when evaluating tillage effects on weeds. A cool spring and a limited selection of available weed control tools also were suggested as possible reasons for high yield losses due to weed pressure in maize and soybean. Interestingly, yield of more competitive barley (*Hordeum vulgare* L.) and red clover (*Trifolium pretense* L.) was not affected by the increased weed pressure in ZT plots.

Some rotational schemes are better suited than others to organic ZT. Diverse crop rotations indirectly impact weed population through tillage effects, because tillage timing and frequency varies with crop species [59,61]. Weed species that are phenologically synchronous with a particular crop species tend to survive and proliferate with that crop [72]. Smith [61] concluded from a three-year study that spring tillage produced weed communities dominated by early emerging spring annual forbs and C4 grasses, whereas fall tillage favored later emerging annuals and C3 grasses. Planting crops with differing phenologies, such as winter wheat *vs.* maize, helps to disrupt crop–weed life cycle synchronies [10], although Anderson [72] reported that alternating two years of a warm season crop with two years of a cool season crop reduced weeds more than alternating cool and warm season crops on a yearly basis in ZT systems managed conventionally. Crop rotation effects also vary with tillage system. Three-year rotations had smaller weed seed banks than two-year rotations under conventional ZT, but this rotation effect was absent under chisel plowing [73]. Likewise, a recent study in transitional organic systems showed that weed seed density in the top 5 cm of soil declined with a more complex rotational scheme [74]. A highly complex nine-year rotation that included a ZT phase to enhance soil health and reduce surface weed seed, alternating two years of cool season (wheat, pea) with warm season (maize, soybean) crops to disrupt phonological crop–weed association, and a perennial forage phase to add N and control perennial weeds was recommended to reduce weed densities in organic conservation tillage systems [10].

Changes in tillage systems may indirectly impact weed populations via altering processes that degrade or destroy weed seeds. Weed seeds remaining on or near the soil surface are subject to destruction via desiccation and herbivore or pathogen attack [73]. Soil fungal and bacterial microorganisms have been shown to be more abundant in ZT *vs.* intensively tilled systems [75], but weed seed response to surface colonization by microorganisms is highly dependent on species [76]. Therefore, weed seed decay may be enhanced by ZT, but the effect will probably vary greatly according to weed species. More research is needed to clarify mechanisms that may lead to enhanced seed decay in organic systems. Surface weed seed removal by insect and small mammal predators from the soil surface is thought to substantially reduce weed seed banks, but predation rates can vary with tillage systems [77]. For example, Menalled *et al.* [78] observed that activity density of granivorous carabids and removal of fall panicum (*Panicum dichotomiflorum Michx.)* and common lambsquarters (*Chenopodium album* L.) seeds were greater in ZT systems when compared to both tilled conventional systems and tilled organic systems. However, such effects vary widely with geographic region and dominant predators, and some studies have shown no differences in predation rates between tilled and ZT fields [79,80].

3.2. Cover Crop Impacts on Weed Populations

Initially, conservation tillage systems were pioneered in conventional cropping systems where herbicides could be used to replace tillage for weed management. Organic conservation tillage systems have relied heavily on high-residue cover crops to suppress emerging weeds. Cover crops suppress weeds by providing a physical barrier, but cover crops also block light and diminish soil thermal cycling, both of which serve as germination cues for many small seeded annual weed species [42,81]. Initial attempts at incorporating cover crops into ZT organic systems generally terminated the cover crop via mowing. For example, Drinkwater *et al.* [82] compared maize yield among organic systems that included a hairy vetch cover crop managed under both tilled and ZT (mowed cover crop) management. Maize yield was lower in the ZT system compared to other organic systems, which was attributed partially to greater weed biomass in the ZT treatment. The authors concluded that some level of tillage was necessary to achieve a viable organic production system using a vetch cover crop.

Feasibility of ZT systems was greatly enhanced with the advent of roller-crimper technology, which enables mechanical cover crop kill, but unlike mowing, leaves cover crop residue anchored to the soil [37,42]. Cover crops killed via rolling-crimping are more resistant to decomposition than mowed cover crops, thus providing extended weed suppression [81]. Mirsky *et al.* [83] demonstrated that effectiveness of rolled-crimped cover crops in suppressing weeds was impacted by cover crop selection, seeding and termination dates, with earlier seeding and later termination resulting in largest production of above-ground biomass. Because termination affects soil surface temperature and light which cue many weed species to germinate and emerge, termination date affected species composition, with later termination selecting for later emerging annuals such as foxtails (*Setaria* spp.) and wild buckwheat (*Polygonum convolvulus* L.). Unlike annuals, perennial weeds such as yellow nutsedge (*Cyperus esculentus* L.) were not affected by cover crop residue. The authors concluded that late termination provided enhanced weed control, but expressed concerns about the effects of late planting on subsequent crop performance. The researchers emphasized the need of including additional tactics such as rotational tillage or crop rotations to combat weed species not easily controlled by cover crops, especially perennial weeds.

Although cover crops primarily inhibit weed growth via physical suppression imposed by surface residue, these crops can also affect weed communities via allelopathy, alteration of nutrient cycles, and enhancement of weed seed decay [84,85]. Rye has long been reputed to produce allelopathic compounds [86,87]. The phytotoxic allelopathic effects produced by rye residues are thought to be primarily due to benzoxazizone compounds. The biosynthesis of these compounds is greater in younger tissues and varies with rye cultivars and environmental factors [88]. In roller-crimper systems, where rye is terminated at a late stage and residues are not incorporated into the soil, allelopathy may have a limited role in weed suppression compared with the physical suppression provided by the vegetative mulch. However, phytotoxins produced by allelopathic crops typically are leached out of surface residue and penetrate the first 2 to 3 cm of soil, where most germinable weed seeds reside [89], suggesting that allelopathy still may be a weed suppression mechanism in rolled-crimped systems.

Cover crops may affect weed community dynamics through alteration of nutrient cycling processes, particularly N cycling [90]. Previous research has shown that weed response to N is species-specific although many weeds prevalent in conventional systems have high-N uptake and utilization capacity [91]. Organic systems typically employ slowly released N sources, such as cover crop residue and manure, which may represent a slight disadvantage to nitrophilous weed species that respond quickly and efficiently to luxury N [81]. Some cover crops used in organic systems can contribute a substantial amount of N to the soil (e.g., hairy vetch), whereas others contribute mostly C (e.g., winter rye). Thus, cover crop species may vary in weed suppressive ability based on N input and also differences in N response by contrasting weed species. For instance, Hayden *et al.* [92] showed that while non-mustard family weed species were suppressed equally by rye alone and rye/vetch, rye alone suppressed mustard family weeds better than rye/vetch. The authors suggested that the mustard family weeds were highly sensitive to N depletion and thus suffered more with rye alone than the non-mustard weed species.

Carbon and N from cover crops may also indirectly influence weed seed banks by altering microbial actions responsible for seed decay. Davis *et al.* [93] observed that giant foxtail (*S. faberi* L.) and velvetleaf (*Abutilon theophrasti* Medicus) seed decay generally was greater in soil from systems with a history of synthetic N inputs than in soil from systems with a history of organic N inputs. These changes appeared to be associated with the differences in the soil microbial community. The authors speculated that using high C:N amendments might result in immobilizing soil N needed for microbial growth. In contrast, another study that determined persistence of smooth pigweed (*Amaranthus hybridus* L.) and common lambsquarters seed in organic *vs.* conventional systems showed no consistent association between seed persistence and system type or microbial biomass [94]. Even within an organic system, the choice of N source may have impacts on weed communities. For instance, Ryan [60] showed that weed seed bank species in organic systems that included manure but not hairy vetch were more similar to conventional system seed bank species (indicative of higher N) than organic systems that excluded manure but included hairy vetch. These differences could have been due to a filtering effect of the hairy vetch, weed seed contamination of manure, or N differences. Understanding effects of organic N and C sources on weed communities is challenging and more research on this topic is needed.

Cover crops may affect weed communities indirectly through influences on vertebrate and invertebrate herbivores that consume weed seeds, because cover crops provide habitat and protection for herbivores [80,95]. Numerous studies have demonstrated a positive correlation between vegetative cover and weed seed predation rates [95–98]. Several previous studies have shown increased weed seed predation rates associated with leguminous cover crops [95–97], but the underlying reasons for this phenomenon remain unclear. Disturbance caused by planting cover crops may be antagonistic to weed seed predation in organic ZT systems in temperate regions, because winter annual cover crops are typically sown at a time that may intersect with the peak activity of many important seed predators, particularly invertebrates [95]. A study conducted to determine the effect of various cover cropping systems on invertebrate seed predators found that the ground-dwelling carabid *Harpalus rufipes* was less abundant in plots that had been recently tilled and planted to cover crops than other comparatively non-disturbed plots [95]. Organic ZT, where the winter annual cover crop is drilled directly into crop residue with minimal disturbance, retain more weed seeds on the soil surface and provide better habitat for seed predators [99,100].

3.3. Complementary Weed Management Strategies

Certain types of weeds such as perennials and large-seeded species will not be adequately suppressed regardless of surface residue quantity produced by a cover crop [99]. Therefore, using cover crop mulch alone to suppress weeds in organic ZT systems will not provide adequate weed control across a crop rotation. Even in conservation tillage systems where limited amounts of tillage can be used, most implements currently available do not function properly in fields with large amounts of surface residue [20]. Shirtliffe and Johnson [41] found that multiple passes with a minimum till rotary hoe provided acceptable weed control and yield protection for pea sown into ZT wheat stubble, but this system included only residue from a previous crop and not rolled-crimped cover crop residue. High residue cultivators have been improved in recent years so that they slice effectively through thick surface residue while creating minimal soil disturbance [101]. In a soybean crop planted into roller-crimped rye, supplemental cultivation with a high residue cultivator reduced weed biomass, but not as effectively as an herbicide application [102]. Mirsky *et al.* [101] observed that using a high residue cultivator in organic soybean reduced weed biomass compared to uncultivated plots, but the reduction in weed biomass was not always associated with increased soybean yield. The authors explained that sometimes weeds may impact crop yield prior to removal if cultivation is not performed in a timely manner. Additional research is needed to successfully integrate supplementary cultivation into high-residue organic conservation tillage systems.

Stale seedbed techniques can be employed to reduce weed populations prior to planting in many conservation tillage systems [20], but this approach is not feasible in organic ZT systems [103]. However, there are weed management strategies in addition to the use of cover crops that could be incorporated into organic ZT for weed control. Collection and/or physical destruction of weed seeds at harvest is an approach that could be incorporated into such systems [104]. Walsh *et al.* [105] developed a mechanical system that destroys weed seeds which are collected during harvesting. Instead of releasing raw chaff, which contains numerous weed seeds, this system diverts the chaff into a ball mill which destroys more than 95% of weed seeds. Alternatively, the chaff can be placed into windrows and burned, which also has been shown to destroy large percentages of captured seed [106]. The limitation of this system is that it is only effective when the predominant weed species mature at the same time as the crop. Another possibility includes forced air to destroy weed seedlings. Forcella [107] described an approach whereby a modified sandblaster was used to bombard common lambsquarters and maize plants with maize cob grit. Results of this study showed that weeds were adequately controlled but maize plants remained uninjured. Research is ongoing to investigate the potential of this concept on a commercially viable scale. Seeding crops at optimal densities can provide substantially increased competition against weeds and may synergistically enhance weed suppressive efforts of cover crops [108]. As mentioned previously, livestock grazing has been used to control weeds [109], and rotations including a perennial forage crop phase in the crop rotation to control perennial weeds in organic ZT systems should be considered.

Previous research has suggested that in conventional crop production systems, herbicides, and to a lesser extent tillage, are strong filters governing the assembly of weed communities [60]. These strong signals lead to more predictable systems that are amenable to technology-driven research and management. Organic ZT systems lack these two strong filters that highly influence weed community assembly processes. Therefore, processes that govern agroecological outcomes are less tightly linked to specific technologies in these systems. These outcomes, such as weed suppression, represent emergent properties of the entire linked system [82]. Consequently, future research aimed at improving weed management in organic conservation tillage and specifically ZT systems should focus on studying processes, or mechanisms, that drive or underlie responses, rather than simply testing technology or individual practices.

4. Organic Conservation Tillage Effects on Soil Quality

Improvement of soil quality has long been a central component of organic farming [110]. Syntheses of published research suggest soil responses to organic production practices are positive with respect to improving soil function through the enhancement of biophysical properties and processes [111,112]. Such soil biophysical improvements are attributed to the emphasis of organic farming on diverse crop rotations, including perennial forages, as well as application of carbon-rich soil amendments [113]. Despite benefits to soil biophysical attributes, organic farming effects on soil organic C (SOC)—a foundational attribute affecting multiple soil properties—are inconclusive due to difficulties comparing organic and conventional systems, a lack of properly defined baseline conditions, and an absence of soil bulk density measurement in many studies [114]. Methodological drawbacks aside, dependence on mechanical cultivation for weed control in organic farming has been identified as a significant barrier to SOC accrual in organic production systems [39]. Tillage contributes to SOC loss by enhancing mineralization and exposing soil to wind and water erosion, and is a leading cause of soil degradation worldwide [115]. Concerns over the reliance of tillage and its documented negative effects on soil quality prompted the International Federation of Organic Agriculture Movements (IFOAM) to adopt standards recommending organic farmers "minimize loss of topsoil through minimal tillage, contour ploughing, crop selection, maintenance of soil plant cover and other management practices that conserve soil" and "should take measures to prevent erosion, compaction, salinization, and other forms of degradation" [116].

Calls within the organic community for minimizing tillage are informed by decades of research documenting soil quality outcomes associated with conservation tillage in systems managed conventionally (*i.e.*, using synthetic agrichemicals). Conservation tillage creates a suitable soil environment for growing a crop by conserving soil, water and energy resources mainly through the reduction in the intensity of tillage and retention of plant residues [117]. Changes in soil condition associated with conservation tillage intensity and increased plant residue retention include increased SOC [118], improved surface physical conditions and plant nutrient status [119,120], and enhanced microbial biomass and activity [121,122]. Such changes in soil condition improve soil function—and thereby soil quality—by reducing erosion, increasing soil water storage potential, and improving nutrient-use efficiency [123–125].

Soil quality responses to organic production practices and conservation tillage suggest that an integration of both management approaches could contribute to synergistic outcomes resulting in substantially improved near-surface soil conditions on organic farms. With this as context, we sought to synthesize published research addressing soil quality attributes in organic conservation tillage systems as a complement to the preceding sections on crop production and weed management. As reviewed below, such research is limited in amount, duration, and geographical scope, yet provides important insights into the trajectory of soil properties under this novel production system.

4.1. Soil Property Responses

The USDA National Agricultural Library Digital Desktop Library (DigiTop) was used to locate published research articles pertaining to organic conservation tillage systems and soil quality [126]. Navigator direct search terms used individually and in combination included organic, organic farming, organic production practices, conservation till(age), minimum till(age), reduced till(age), no-till(age), zero-till(age), soil quality, soil health, and soil properties. Fifty-six articles were identified pertinent to the topic, but only 14 included soil data specific to organic conservation tillage systems, and only one included data from an organic ZT system. Given the lack of published soils-related data on organic ZT, we opted to synthesize data from organic conservation tillage systems. In most studies, conventional and conservation tillage systems were contrasted under equivalent forms of organic management in Western Europe. Findings are synthesized below in four sections: Soil organic carbon, soil biological attributes, soil structural attributes, and soil pH and plant nutrients.

4.1.1. Soil Organic Carbon

Compiled results across six studies underscored potential benefits from tillage reductions for conserving SOC in organic production systems. Soil organic C under conservation tillage was numerically greater than conventional tillage in all studies for near-surface depths, with absolute and relative differences between treatments averaging 1.1 g C kg^{-1} and 6%, respectively (Table 1). Differences in SOC between conservation and conventional tillage for surface depths ranged from 0.2 to 4.5 g C kg^{-1}, and were strongly associated with treatment duration (r = 0.98; $P \leq 0.01$), which varied from one to six years. Soil organic C was greater under conservation than conventional tillage below 10 cm for two studies (Range = 0.3 to 0.9 g C kg^{-1}) [127–129], while a third study in France [130] found greater SOC under conventional tillage at 15–30 cm. Though reported studies concentrated on SOC, Lewis *et al.* [131] found labile C 14% greater under conservation than conventional tillage during the third year of a transition to organic management.

Management drivers affecting soil C inputs were similar between conservation and conventional tillage treatments among reported studies, thereby eliminating potential confounding effects of management that commonly plague comparisons between organic and conventional production systems [114]. Accordingly, one can conclude there is a differential treatment effect on SOC, with conservation tillage providing a clear advantage over conventional tillage under organic management. However, stronger statements regarding the effect of conservation tillage on SOC are compromised by the fact that none of the studies reported baseline SOC, nor were SOC results expressed on a mass basis due to the absence of soil bulk density data (with the notable exception by Emmerling [132]). As expressed elsewhere [114,133], these two drawbacks severely limit the capacity to accurately discern management effects on SOC.

Table 1. Effects of conventional and conservation tillage practices on soil organic C for organically managed production systems.

Location	Treatment duration (yr)	Depth (cm)	Soil organic C ($g\ C\ kg^{-1}$): Tillage treatment: Conventional tillage	Conservation tillage	Difference: Absolute (Cons.–Conv.)	Relative (%)	Reference
Rock Springs, PA, USA	3	0–15.2	13.5	15.5	2.0	15 [a]	[131] [b]
Borovce, Slovak Republic	2	2–20	13.1	14.3	1.2	9	[134]
Mainz, Germany	3	0–15	17.6	19.1	1.5	9	[127]
		15–25	16.4	16.7	0.3	2	
Frick, Switzerland	3	0–10	21.1	23.4	2.3	11	[128]
		10–20	20.8	21.7	0.9	4	
Frick, Switzerland	6	0–10	21.6	26.1	4.5	21	[129]
		10–20	21.4	21.8	0.4	2	
Lyon, France	1	0–15	11.8	12.0	0.2	1	[130]
		15–30	11.8	10.0	(1.8)	(15)	
Mean					**1.1**	**6**	

[a] Relative difference compares soil organic C difference between conservation and conventional tillage to the quantity in conventional tillage; [b] Soil organic C calculated from soil organic matter content assuming 58% C in the latter.

4.1.2. Soil Biological Attributes

The abundance and diversity of soil biota affect water- and nutrient-use efficiencies and, in turn, agroecosystem resilience [135]. Microbial biomass C reflects an estimate of the soil microbial population and its potential activity under ideal laboratory conditions, and is considered an early indicator of treatment effects on soil C pools [136]. Five organic studies, all in Western Europe, found greater microbial biomass C under conservation tillage compared to conventional tillage by an average 64 mg C kg^{-1}, reflecting a 7% difference between treatments (Table 2). In contrast to SOC results, microbial biomass C was not consistently greater under conservation tillage at lower depths, as Weber and Emmerling [127] found 11% more microbial biomass C under conventional than conservation tillage at 15–25 cm, while Vian *et al.* [130] found 47% more microbial biomass C at 15–30 cm under conventional than conservation tillage. Additionally, tillage effects at an experiment near Frick, Switzerland [128,129] suggested moderate stratification of microbial biomass C under conservation tillage, as differences in microbial biomass C between conservation and conventional tillage were 3–5 fold greater at 0–10 cm than 10–20 cm. Microbial quotient, a surrogate measure of soil biological fertility calculated as the ratio of microbial biomass C to SOC [137], was numerically greater under conservation than conventional tillage in four of five organic studies, though mean differences across studies were small (Conservation = 3.5, Conventional = 3.4; data not shown). Soil enzyme activities and microbial biomass C in these same studies were found to respond similarly to tillage treatments. Alkaline phosphatase activity at a 0–15 cm soil depth was numerically greater under conservation compared to conventional tillage in a study near Mainz, Germany [132]. Dehydrogenase activity was significantly greater under conservation than conventional tillage at a 0–10 cm soil depth three years after study implementation [128], while significantly greater activity of the same enzyme extended to a 0–20 cm soil depth under conservation tillage following six years of treatment effects [129].

Earthworms occupy an important role among soil biota by manipulating soil physical properties and redistributing organic matter throughout the soil matrix [138]. Earthworms also are highly sensitive to indirect effects from mechanical disruption (e.g., predation, desiccation), and accordingly, are responsive to changes in tillage management [139]. Organic studies in the U.S. and Western Europe found consistent increases in earthworm abundance under conservation tillage (Table 3). Across studies, there was an average of 53 more earthworms m^{-2} under conservation than conventional tillage, with differences between tillage treatments ranging from 5 to 134 earthworms m^{-2}. Differences in earthworm biomass between tillage treatments were less pronounced and inconsistent across studies, with an average of 15 g m^{-2} more earthworm biomass under conservation than conventional tillage, but greater earthworm biomass under conventional tillage at research sites in Switzerland and France (Table 3). Organic ZT treatments, included at three sites in France [23], resulted in greater earthworm numbers and biomass compared to both conservation (*i.e.*, reduced) and conventional tillage.

Table 2. Effects of conventional and conservation tillage practices on microbial biomass C for organically managed production systems.

			Microbial biomass C (mg C kg^{-1})				
			Tillage treatment		Difference		
Location	**Treatment duration (yr)**	**Depth (cm)**	**Conventional tillage**	**Conservation tillage**	**Absolute (Cons.–Conv.)**	**Relative (%)**	**Reference**
Borovce, Slovak Republic	2	2–20	766	862	96	13 [a]	[134]
Mainz, Germany	3	0–15	323	420	97	30	[127]
		15–25	294	261	(33)	(11)	
Frick, Switzerland	3	0–10	780	996	216	28	[128]
		10–20	754	800	46	6	
Frick, Switzerland	6	0–10	801	1049	248	31	[129]
		10–20	799	869	70	9	
Lyon, France	1	0–15	293	308	15	5	[130] [b]
		15–30	375	200	(175)	(47)	
Mean					**64**	**7**	

[a] Relative difference compares microbial biomass C difference between conservation and conventional tillage to the quantity in conventional tillage; [b] Microbial biomass C values averaged by clod type and interpolated from graph.

Table 3. Effects of conventional, conservation, and no-tillage practices on earthworm numbers and biomass for organically managed production systems.

Location	Treatment duration (yr)	Depth (cm) [a]	Conventional tillage	Conservation tillage	No-tillage	Absolute (Cons.–Conv.)	Relative (%)	Reference
			- - - - - - Earthworms (individuals m^{-2}) - - - - - -					
			- - - - Tillage treatment - - - -			- - - - - Difference - - - - -		
Mills River, NC, USA	3		6	140	.	134	2233 [b]	[140] [c]
Borovce, Slovak Republic	2	0–30	54	134	.	80	148	[134]
Mainz, Germany	3	0–15	12	27	.	15	125	[127] [d]
Frick, Switzerland	3	0–20	81	112	.	31	38	[128]
Rhone Alpes, France	2		20	25	55	5	25	[23] [e]
Pays de la Loire, France	1		15	25	50	10	67	
Brittany, France	3		50	145	160	95	190	
Mean						**53**	**404**	
			- - Earthworm biomass (g m^{-2}) - -					
Borovce, Slovak Republic	2	0–30	42	88	.	46	109	[134]
Mainz, Germany	3	0–15	12	27	.	15	125	[127]
Frick, Switzerland	3	0–20	67	46	.	(21)	(31)	[128]
Rhone Alpes, France	2		20	15	30	(5)	(25)	[23]
Pays de la Loire, France	1		10	20	40	10	100	
Brittany, France	3		15	60	85	45	300	
Mean						**15**	**96**	

[a] Depth not specified for studies using formalin or mustard suspension extraction methods; [b] Relative difference compares earthworm number or biomass difference between conservation and conventional tillage to the quantity in conventional tillage; [c] Counts include both adult and juvenile earthworms. Mean values for each tillage system calculated across rotations. Data interpolated from figure; [d] Data interpolated from figure; [e] Values included from October 2006 (Sites A and B) and March 2006 (Site C).

Outcomes from the limited number of organic studies suggest that tillage reductions positively affect soil biota compared to conventional tillage. Both microbial biomass and macrofauna are positively influenced by surface application of organic matter [125,141], and when combined with a reduction in soil disturbance through conservation tillage, outcomes summarized in Tables 2 and 3 are not unsurprising. Establishing potential linkages between increased soil biota abundance and improved soil function under organic conservation tillage represents a critical research need, but will likely require long-term studies and a commitment to continued monitoring to elucidate such relationships.

4.1.3. Soil Structural Attributes

Soil structural attributes are influenced by the amount and type of organic matter amendments applied to soil, as well as the intensity and frequency of physical disruption by tillage [142]. Because soil structure is a reflection of the arrangement of particles and pores in the soil matrix, it directly affects air and water transfer, and accordingly, production and environmental regulation functions of soil [143]. To date, evaluations of soil structural attributes in organic conservation tillage systems have focused on soil aggregate stability, aggregate size distribution, and soil bulk density.

A four-year study in central France contrasting four tillage treatments under organic management found traditional moldboard plowing contributed to a more porous soil structure than reduced and ZT [144]. Modification of soil structure by tillage treatments in this study was reflected through significantly lower soil bulk density in shallow and traditional moldboard plowing compared to ZT and other conservation tillage treatments at 10–15 cm. No differences in soil bulk density were observed among tillage treatments at 15–20 cm, however. Emmerling [132] observed significantly lower soil bulk density at 0–15 and 0–25 cm soil depths under traditional and two-layer plow treatments compared to a layer-cultivation treatment near Mainz, Germany. Interestingly, increased earthworm abundance under organic conservation tillage treatments was not found to affect soil structural attributes [23], though the authors acknowledge more time was necessary to assess effects of biological activity on soil physical attributes.

While some studies have found more compact soil physical conditions under organic conservation tillage treatments in the short-term, others have observed improvements in aggregate stability. In a tillage transition study in western New York, Mochizuki *et al.* [145] found rolled mulch to increase soil wet aggregate stability by 4% over that observed in a rye stubble treatment during one year of the study. Emmerling [132], using aggregate mean weight diameter (MWD) as a surrogate for stability, found two-layer plow and layer-cultivation treatments possessed smaller aggregate MWD (representing more stable aggregates) compared to traditional moldboard plow at the 0–25 cm soil depth.

4.1.4. Soil pH and Plant Nutrients

Assessments of soil solution chemistry in organic conservation tillage studies have largely focused on pH responses to applied treatments. Research results at three and six years after treatment establishment near Frick, Switzerland indicated significantly lower soil pH under conservation tillage compared to conventional tillage at a 0–10 cm soil depth [128,129]. Furthermore, comparison of soil pH over time in this study demonstrated significantly lower pH under conservation tillage in 2008 when compared to baseline conditions in 2002 [129]. This outcome was purportedly caused by surface accumulation of organic acids and leaching of basic cations to deeper depths. However, not all studies investigating soil pH responses to organic conservation tillage systems have observed greater acidification under conservation tillage. Lewis *et al.* [131] observed greater soil pH under conservation tillage compared to conventional tillage in an organic transition study near Rock Springs, PA, USA, while Lahocká *et al.* [134] found no difference in soil pH between tillage treatments in a similar conversion study in the Slovak Republic. Though results are limited, compiled results for surface depths (0–20 cm) across the reported studies showed a minimal reduction in soil pH from conservation tillage (Conservation tillage = 7.10 ± 0.57; Conventional tillage = 7.12 ± 0.64; data not shown).

Long-term use of conservation tillage can contribute to near-surface accumulation of plant nutrients and greater nutrient mineralization potential in non-organic production systems [146,147]. Similar findings have been found under organic management for plant available P, Zn, and exchangeable cations (Ca, Mg, K), with a strong trend toward nutrient stratification in near-surface depths under conservation tillage [127,129]. In a long-term study in central Pennsylvania, USA, N mineralization at a 0–5 cm soil depth was greater under an organic ZT treatment compared with moldboard plow, but was not different between tillage systems at a 5–20 cm soil depth [81]. A contrast between conventional ZT and organic conservation tillage systems in central Montana found greater potentially mineralizable N at 0–60 cm in the latter [15]. While these findings are encouraging from the standpoint of N supplying potential in organic conservation tillage systems, challenges remain to develop effective management controls for matching soil N release with plant uptake in time and space. Failure to develop such management controls may contribute to enhanced N loss [81].

4.2. Synthesis and Recommendations

Reduced physical disturbance by tillage in organic production systems creates a unique soil environment that can affect soil function and, in turn, agroecosystem performance. Published studies reviewed here suggest effects of organic conservation tillage systems on soil properties are concentrated in near-surface soil depths (<10 cm), thereby contributing to increased stratification of nutrients and biological activity. Compared to conventional tillage, conservation tillage under organic management enhances SOC concentration, soil microbial biomass, enzyme activity, select plant nutrients, N mineralization potential, and earthworm abundance. Conversely, conservation tillage effects on soil structural attributes and pH are mixed or unchanged compared to conventional tillage. While conclusions are clearly tentative due to a limited number of long-term studies, organic conservation tillage systems appear to foster a surface soil environment with enhanced nutrient cycling capacity. Such an outcome—if confirmed through future evaluations—possesses important implications for weed and nutrient management in organic production systems [148,149].

It is important to acknowledge reviewed studies focused on near-surface soil responses to applied treatments, and while certainly justified from the standpoint of inferring treatment effects on soil erosion, water infiltration, and nutrient conservation [150], the lack of characterization of subsoil conditions and an absence of soil bulk density data compromises our capacity to accurately resolve treatment effects on soil nutrient stocks [112,151]. Supplementing whole-profile assessments with soil bulk density measurements in future evaluations will strengthen conclusions regarding organic conservation tillage system effects on soil quality.

5. Conclusions

Research on organic conservation tillage has expanded from a limited effort in the early 1990s to involve numerous research teams in both North America and Europe. Moreover, field studies no longer are confined to those two continents but have expanded to include others [152]. Efforts are underway to develop organic ZT systems where tillage is eliminated completely when certain field and horticultural crops are grown organically. Several potential benefits can result if adoption of conservation tillage and particularly ZT practices is successful and have been identified. We focused our discussion on the agronomic, weed, and soil quality impacts which can result when ZT and other conservation tillage practices are adopted. Other possible advantages of replacing conventional with conservation tillage systems, particularly ZT, on nonrenewable energy use and other factors not considered in this paper are described elsewhere [153].

Cover crops are an important component of organic ZT systems. Previous research has provided baseline data on the quantity of cover crop residue needed to suppress annual grass and broadleaf weeds. Considerable work still is needed to answer a host of basic agronomic questions related to cover crop species adaptation and selection, management for maximum above-ground dry matter production, and termination method for timely and effective kill with minimum soil disturbance. The impact of cover crops on nutrient cycling and management of weeds as well as disease and insect pests in organic ZT and other conservation tillage systems is poorly understood, even though this knowledge is essential for the successful adoption of these systems by organic farmers. Economic comparisons between organic ZT and other conservation tillage systems that utilize cover crops and conventional tillage systems will be needed as agronomic questions relating to these conservation tillage systems are answered.

Developing more effective supplementary weed control options, such as livestock grazing or low-disturbance mechanical weed or weed seed destruction, may enhance the feasibility of organic ZT and other conservation tillage systems. Much of the research conducted to examine effects of tillage intensity on weed population dynamics and soil attributes has been conducted in conventional systems, where application of synthetic agrichemicals such as fertilizer and herbicides represent strong filters on the assembly of biotic communities including weeds and soil macro- and microfauna. Therefore, additional research about conservation tillage effects on weed communities and soil biological, chemical, and physical properties should be conducted under organic management conditions. Focusing on understanding underlying processes as well as effects of tactics may help to produce information that is widely applicable and not just pertinent to particular environments or locations. This research is lacking, particularly in regards to organic ZT systems.

Outcomes synthesized from a limited number of short-term studies suggest organic conservation tillage systems create a soil environment with improved nutrient cycling capacity. This conclusion is based on observations of greater SOC concentration, soil microbial biomass, enzyme activity, select plant nutrients, N mineralization potential, and earthworm abundance under organic production systems where a reduction in tillage was imposed. While these changes in soil attributes confer an improvement in soil quality compared to practices employing conventional tillage, much work remains to verify whether organic conservation tillage systems effectively address soil degradation concerns associated with organic farming [114]. Future clarification will require additional evaluations and a commitment to more rigorous assessments, including characterization of subsoil conditions and inclusion of soil bulk density measurements. Special effort should be made to include organic ZT systems in this effort since impacts could be greatest when tillage is eliminated completely in organic cropping systems.

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Conflict of Interest

The authors declare no conflict of interest.

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