Current Status and Soil Biology Impacts of Organic Conservation Tillage in the US Great Plains

Shabeg S. Briar, Patrick M. Carr, Greta G. Gramig, Fabian D. Menalled, and Perry R. Miller

Introduction

Conservation-tillage practices are replacing conventional-tillage practices throughout semiarid regions in North America and elsewhere because of reductions in soil erosion, increases in stored soil water and organic matter, carbon sequestration, and other ecosystem services. For example, over 50% of the area used for dryland crop production is currently under no-tillage (NT) management in a major portion of the US northern Great Plains (Hansen et al. 2012). These results have spurred interest among farmers and researchers in North America and Europe in replacing conventional tillage with NT farming methods in organic settings so that the benefits which result following this conversion can occur in such systems. Reflecting this, several papers have recently been published which describe efforts by researchers to develop NT organic farming systems (Carr et al. 2013b; Delate et al. 2012; Halde and Entz 2014, Halde et al. 2015; Mischler et al. 2010; Nord et al. 2011).

Research on organic farming has focused on rotational-NT systems, where tillage is not used when growing some crops but is employed when growing others

S. S. Briar
Centre for Innovation, Olds College, Alberta, Canada
e-mail: sbriar@oldscollege.ca; shabeg.briar@montana.edu

P. M. Carr (✉)
Central Agricultural Research Center, Montana State University, Moccasin, MT, USA
e-mail: patrick.carr@montana.edu

G. G. Gramig
Department of Plant Sciences, North Dakota State University, Fargo, ND, USA
e-mail: greta.gramig@ndsu.edu

F. D. Menalled · P. R. Miller
Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT, USA
e-mail: Menalled@montana.edu; pmiller@montana.edu

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(Halde et al. 2014; Mirsky et al. 2012). Success has been reported following adoption of organic rotational-NT systems in subhumid and humid regions of North America (Moyer 2011; Reberg-Horton et al. 2012), and soybean (*Glycine max* L.) production seems particularly suited to rotational-NT (Carr et al. 2013b). Conversely, only mixed success has been reported in drier regions where grain yields were depressed when wheat was grown in an organic rotational-NT system compared with an organic tilled system in Manitoba, Canada (Vaisman et al. 2011). Similarly, grain/seed yields were reduced to >90% when buckwheat (*Fagopyrum esculentum* Moench) and dry bean (*Phaseolus vulgaris* L.) were grown in organic rotational-NT systems compared with tilled systems in the US northern Great Plains (Carr et al. 2013b). Weed competition, lack of plant-available nitrogen, and soil-water deficits have been suggested as explaining the poor performance when crops are grown using organic rotational-NT compared with tilled systems in some environments (Carr et al. 2012; Delate et al. 2012; Vaisman et al. 2011).

Vegetative mulches are relied on heavily to suppress weeds prior to planting grain and seed crops in organic rotational-NT systems. Both broadleaf and grass species have been evaluated for use as cover crops (Shirtliffe and Johnson 2012; Carr et al. 2012; Silva 2014), but the most widely grown cover crops have been winter rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) in organic rotational-NT systems (Mirsky et al. 2009, 2012; Mischler et al. 2010; Reberg-Horton et al. 2012). A weed-suppressive, vegetative mulch is created after cover crops are terminated using a roller-crimper (i.e., a steel cylinder with blunt metal blades oftentimes mounted in a chevron pattern) or a mower (Silva 2014). Typically, a winter rye cover crop is rolled-crimped, and then soybean is direct seeded into the vegetative mulch created by the killed cover crop (Nord et al. 2011). Another common practice has been to direct seed maize *(Zea mays* L.) into a vegetative mulch produced by rolled-crimped hairy vetch (Moyer 2011), although the hairy vetch cover crop/maize grain crop sequence has not always been successful (Delate et al. 2012).

It is essential that adequate amounts of aboveground dry matter are produced by cover crops so the vegetative mulch which results following rolling-crimping can suppress weeds adequately. Previous research suggested that somewhere between 5000 and 6000 kg ha^{-1} of vegetative mulch was needed to suppress annual grass weeds and perhaps as much as 12,000 kg ha^{-1} to suppress annual broadleaf weeds (Teasdale 1996). More recently, excellent weed suppression occurred when at least 7000 kg ha^{-1} of the aboveground dry matter was produced by cover crops (Reberg-Horton et al. 2012). Even so, Nord et al. (2011) argued that it was not reasonable to expect a vegetative mulch produced by killed cover crops to be adequate in providing effective weed control without additional tactics being used, particularly in the case of established perennial weeds. We have observed Canada thistle (*Cirsium arvense* (L.) Scop.) emerging through 45-cm-thick wheat straw placed on the soil surface to prevent weed emergence and growth (unpublished data). Rather, the vegetative mulch produced by killed cover crops should be one of several practices used for adequate weed suppression in an organic rotational-NT system.

Organic Continuous-NT Systems

Continuous-NT is common in the US northern Great Plains and similar regions in environments where synthetic fertilizers and pesticides are used. Continuous-NT offers many soil conservation and other ecosystem services compared with tilled systems (Carr et al. 2009; Tanaka et al. 2010). There are environments where persistent wet soils and other factors favor periodic tillage (Hill 1998; Omonode et al. 2006), and there is evidence that some ecosystem services can be maintained when intermittent tillage is used in otherwise continuous-NT systems (Venterea et al. 2006). Other research indicates that some ecosystem services are compromised when even occasional tillage is used. For example, Wortmann et al. (2008) found that a single tillage operation reduced arbuscular mycorrhizal populations by almost 50% when compared with continuous-NT.

Few efforts have been made to eliminate tillage completely when growing crops organically, and results are far from encouraging. Halde et al. (2015) reported results of a 6-year study conducted at Carmen, Manitoba, Canada, where an organic continuous-NT system was compared with an organic tilled system as well as conventional NT and tilled systems where synthetic fertilizers and pesticides were used. Grain yield was 13% lower in the organic continuous-NT system compared with the organic tilled system by the 2nd year of the study. By the 5th year of organic continuous-NT, grain yield had dropped by almost 67%. Severe weed pressure in continuous-NT plots forced abandonment of the study in the 6th year. The researchers concluded that organic continuous-NT was possible over a 4-year period in some environments, though they acknowledged that grain yield would be reduced in this system compared with organic tilled systems.

We completed a study recently in southwestern North Dakota to determine if organic continuous-NT was possible in the US northern Great Plains. Grain yield depression of crops occurred earlier in the organic continuous-NT system in our study than in the earlier Canadian research reported by Halde et al. (2015). For example, no difference in grain yield was detected in the 3rd year of organic continuous-NT compared with tilled treatments in the Canadian study, whereas grain study was depressed by over 40% in the NT plots in our study. However, grain yield reductions of over 60% occurred by the 5th year in both studies, and severe weed infestations in organic continuous-NT resulted in termination of both studies by the 6th year. Failure of rolled-crimped cover crops to provide adequate amounts of vegetative mulch to suppress weeds in some years was reported by Halde et al. (2015), and a similar problem was encountered in our study (unpublished data).

A shift from annual to perennial weed species frequently occurs when tillage is eliminated from a cropping system (Carr et al. 2013a; Melander et al. 2013). Dandelion (*Taraxacum officinale* Weber) became prevalent in organic continuous-NT plots relative to organic tilled plots in the 6-year study conducted at Carmen (Halde et al. 2015). Likewise, infestations of perennial weeds were common in organic continuous-NT plots in our study, particularly over time. In our study, late-season evaluation indicated that dandelion along with Canada thistle and field bindweed was particularly prevalent in continuous-NT plots but was largely absent in tilled plots. Among perennial grass species, crested wheatgrass (*Agropyron cristatum* [L.] Gaertn.), fescue (*Festuca* spp.), and foxtail barley (*Hordeum jubatum* L.) dominated the weed spectrum. This shift to a greater abundance of perennial weed species in organic NT systems may explain partially why Mirsky et al. (2012) and others (Brainard et al. 2013) suggested that organic continuous-NT cannot be achieved.

Annual species tend to dominate the weed spectrum in tilled systems. Barnyard grass (*Echinochloa crus-galli* [L.] Beauv.), green foxtail (*Setaria viridis* [L.] Beauv.), shepherd's purse (*Capsella bursa-pastoris* [L.] Medik.), and wild buckwheat (*Polygonum convolvulus* [L.]) were among the annual species that dominated the weed population in tilled plots in the study reported by Halde et al. (2015), as well as in our study. While annual species contributed a much smaller proportion to the total weed density in NT compared to tilled plots, downy brome along with prickly lettuce (*Lactuca serriola* L.) and tansymustard (*Descurainia pinnata* [Walt.] Britt.) occurred in relatively large numbers in organic continuous-NT plots in our study.

It is worth noting that an integrated weed management program was used in both studies where organic continuous-NT was compared to organic tilled systems. In addition to the production of a vegetative mulch produced by cover crops, sheep (*Ovis aries*) grazed plots every 2 (our study) to 3 (Canadian study) years during selected periods when cover and grain crops were not grown to suppress weeds. Sheep grazing has been used for weed control in cropping systems in the US northern Great Plains (Barroso et al. 2015; Hatfield et al. 2007), but only recently within the context of organic systems (McKenzie et al. 2016). Further, a 20% acetic acid solution was applied prior to planting grain crops in our study, beginning in the 2nd year. In spite of these practices, weed infestations forced abandonment of both studies by the 6th year of organic continuous-NT. These results indicate that organic continuous-NT is not possible presently, even when using multiple weed control tools. However, numerous studies have demonstrated that rotational-NT can be used successively when growing field crops organically (Carr et al. 2013b, Delate et al. 2012; Halde et al. 2014; Halde and Entz 2014; Mischler et al. 2010; Mirsky et al. 2012; Nord et al.; Reberg-Horton et al. 2012). Adoption of rotational-NT is a viable strategy for organic farmers wishing to transition from conventional-tillage systems to conservation-tillage systems so that soil-water conservation and other ecosystem services can be realized.

Conservation-Tillage Impacts on the Soil Food Web

Soil organisms contribute to a wide range of ecosystem services associated with crop production including soil aggregate formation, nutrient cycling, immobilization of toxic compounds, nitrogen fixation, carbon sequestration, and pest suppression (Kibblewhite et al. 2008; Stirling 2014). The processes contributing to these ecosystem services are the result of different assemblages of fauna and flora comprising the soil biological community. The interaction of these organisms in the soil food web, in contrast to their functioning in isolation, is a fundamental concept that was first proposed by Hendrix et al. (1986) and later modified by Kibblewhite et al. (2008).

The sustainability of organic farming depends on the set of plant and animal production practices that emphasize reliance on renewable biological processes, including the cycling of nutrients through the decomposition of cover crops, animal manures, and/or other compounds (Moyniham 2010). Soil food webs in organic farming systems generally are more diverse in species richness and abundance than in systems where synthetic fertilizers and pesticides are used, and the incorporation of plant- and animal-derived organic amendments is aimed at soil food web enhancement. Soil food webs in organic farming systems also play a fundamental role in natural pest regulation or suppressiveness (Ferris et al. 2001; Mäder et al. 2002; Aude et al. 2004; Moyniham 2010).

Soil health is presumed to be the direct expression of the aggregate function of soil macro- and microcommunities which, in turn, are dependent on the physical and chemical conditions of the soil habitat. Any factor affecting a function performed by one group of organisms may affect the functions of other groups. For example, while bacteria and fungi are the primary decomposers in any agroecosystem, fungi dominate decomposition processes in undisturbed soils, while bacteria dominate these same processes in disturbed environments. Therefore, the adoption of conservation-tillage practices favors fungi taking the dominant role in decomposition processes with bacteria taking a secondary role. Similarly, macrofauna (such as earthworms) dominate higher trophic levels in NT systems, while smaller fauna like enchytraeid worms dominate in tilled systems.

Tillage-induced changes to physical and chemical soil properties impact biological activities directly (Zuber and Villamil 2016). Understanding the impacts of tillage practices on soil organisms enables one to select farming practices which protect and sustain biodiversity and maintain ecosystem processes and services (Bertrand et al. 2015; Roger-Estrade et al. 2010; Temme and Verburg 2011). There is a paucity of published information on conservation-tillage impacts on the soil food web in organic farming, so discussions of the potential benefits of tillage reductions on the soil food web health must occur irrespective of the farming system. Further, while current discussions on the soil community at micro-, meso-, and macroscales use biological metrics that are common in the literature, it should be acknowledged that the biological community is more complex and taxonomically diverse than might be inferred. Nevertheless, discussion on the impact of conservation tillage on the soil biological community should elucidate the likely impacts that conservation-tillage practices will have if adopted by organic farmers.

Effect of Conservation Tillage on the Soil Microbial Community

Conservation tillage generally increases soil microbial activity compared to conventional tillage. For example, Gonzalez-Chavez et al. (2010) observed a significant increase in microbial biomass following the adoption of NT, and several studies indicated that soil microbial activity was affected negatively by tillage (Hussain et al. 1999; Kladivko 2001; Sagar et al. 2001; Jinbo et al. 2007). A recent meta-analysis of 62 different studies indicated that microbial biomass and enzyme activities were higher following conversion to NT compared with tilled systems (Zuber and Villamil 2016). Likewise, reductions in tillage and not just complete elimination (as in continuous-NT) increased enzyme activity and microbial biomass. These studies provided compelling evidence that microbial activity and biomass will be enhanced following adoption of NT and other conservation-tillage practices on organic farming systems.

Applications of organic amendments enhance the soil microbial community (Gunapala and Scow 1998; Freckman 1988; Griffiths et al. 1994; Bulluck et al. 2002; Briar et al. 2011). Determining the impact of these amendments on the soil food web is difficult since they typically are incorporated by tillage which has deleterious impacts on the soil microbial community, as previously discussed. Arbuscular mycorrhizal fungi (AMF) are extremely sensitive to soil disturbance, with even moderate tillage completely disrupting the hyphal networks created by this fungal group. This impact on the AMF community has serious repercussions to organic farming since AMF provide ecosystems services related to phosphorus uptake and aggregate stability and are especially important in less intensive agricultural systems (Kabir 2005).

Numerous studies indicate that conservation tillage favors AMF species richness and diversity, spore density, and root infection compared to tilled systems (Jansa et al. 2002; Yang et al. 2012; Köhl et al. 2014; Wetzel et al. 2014). Therefore, negative effects of tillage on AMF are anticipated when used in organic farming systems. Little work has been conducted on the impact of tillage on AMF in environments managed organically. The impact of cultivation on AMF communities under reduced and conventional moldboard plow tillage in an organic farming system was compared in central Europe (Säle et al. 2015). Both AMF spore density and species richness were significantly higher in the top layer of the soils under reduced tillage compared to the cultivated plots.

Impact of Tillage on Nematodes

Nematodes comprise a large fraction of soil microfauna which, in turn, make up a significant portion of the total faunal biomass in agricultural soils (Bardgett and Griffiths 1997; Stirling 2014). Use of ecological indices based on the nematode community analysis for indicating soil food web dynamics has been documented by many researchers (Briar et al. 2007; Sánchez-Moreno et al. 2009; DuPont et al. 2009; Ferris et al. 2012). External organic inputs in the form of compost, animal manures, and cover crops increase energy availability for soil microbes, thereby enhancing microbial activity and biomass, including those of nematodes (Lundquist et al. 1999; Gunapala and Scow 1998; Alon and Steinberger 1999). Therefore, microbial grazers like bacterivorous and frugivorous nematodes respond positively to additions of organic matter to the soil (Ferris and Bongers 2006).

These nematodes make significant contributions to the soil nutrient pool as well as regulate nutrient release into the soil as they graze on soil microbes (Ingham et al. 1985).

Adding organic amendments to the soil enhances population densities of beneficial free-living nematodes in the soil (Wang and McSorley 2005; McSorley et al. 2009). Results of a long-term study in Ohio showed that applications of composted animal manures or hay crop incorporation led to an increase in beneficial free-living nematodes feeding on bacteria and fungi in environments managed organically compared to environments where synthetic fertilizers and pesticides are used (Briar et al. 2007, 2011). However, there was no corresponding increase in large-size predatory or omnivorous nematodes at higher trophic levels in the organic farming system. Consequently, higher trophic links in the soil food web were similar in both systems. Frequent tillage during preparation of the seedbed, mixing of organic manures and cover crops, and cultivation for weed control were likely detrimental to the higher trophic groups. Similar declines in population levels of tillage-sensitive nematode trophic groups occurred in other studies (Fiscus and Neher 2002; Freckman and Ettema 1993; López-Fando and Bello 1995).

The reliance of tillage in organic farming systems appears to be counterproductive to the beneficial effects resulting from additions of organic amendments and cover crops to the soil and the natural progression of the soil food web toward maturity. The higher abundance of beneficial nematodes feeding on bacteria and fungi decomposers is partially offset by the negative impact on the soil microbial community during and after incorporation by tillage. Adoption of conservation-tillage systems and particularly NT could further enhance soil food web nutrient mineralization and maturity (Ferris and Bongers 2006; McSorley et al. 2009; Sánchez-Moreno et al. 2009).

Impact of Tillage on Soil Meso- and Macrofauna

The predominant meso-fauna in the soil are enchytraeids and a variety of collembolans, mites, and small insects collectively known as micro-arthropods, while macrofauna include millipedes, centipedes, spiders, termites, ants, scorpions, and earthworms (Stirling 2014). In general, the higher abundance and diversity of soil biota under conservation-tillage systems can be attributed to the accumulation of crop residues on or near the soil surface, as well as their regulation of both soil temperature and water. The accumulation of crop residues and organic matter in surface layers creates a favorable feeding condition for topsoil-dwelling species (El Titi 2003; Henneron et al. 2015). Surface residues also provide physical protection to shallow surface dwelling micro-arthropods from predators, as well as slow down the rate of soil drying in spring and freezing in winter. This impact on lengthening soil drying rates and buffering soil temperature extends the active period of micro-arthropods, including mites.

Among the soil invertebrate animals, earthworms occupy an important role among soil biota by manipulating soil physical properties and redistributing organic matter throughout the soil matrix, and conservation-tillage practices tend to support higher densities of earthworms (Edwards and Bohlen 1996; Reeleder et al. 2006). Earthworm abundance and biomass were reported to be higher in NT soil, particularly when cover crops were grown, compared with tilled soil, regardless of the crop species grown (Birkas et al. 2004; Chan 2001; Eriksen-Hamela et al. 2009; Metzke et al. 2007). However, earthworm abundance was impacted by the magnitude of tillage, depth of residue burial, and timing of the tillage operations, as well as soil, crop, and climate factors which can sometimes override the impacts of tillage. For example, reduction in earthworm population and biomass due to tillage was higher in finer-textured soils than sandy soils (Joschko et al. 2009; Menalled et al. 2007).

Suggestions for Future Research

Research on the impact of adopting conservation-tillage practices and particular NT in organic farming on the soil food web is limited. Carr et al. (2013a) reviewed research focusing on the effect of conservation tillage in organic farming systems in the USA and Western Europe. Across these studies, there was higher abundance of earthworms under conservation than conventional tillage. Differences in earthworm biomass between tillage treatments were less pronounced and inconsistent across studies, with an average earthworm biomass higher under conservation than conventional tillage in some instances but greater earthworm biomass under conventional tillage in others.

Future research is needed which quantifies the impact of adopting organic rotational-NT on soil micro- and macrofaunal and floral communities, since recent research indicates that organic continuous-NT is not possible using present knowledge and technology. This is particularly true in the US Great Plains and similar semiarid regions, where organic rotational-NT has clear advantages to tilled systems in soil-water conservation and where research on the impacts of rotational-NT on the soil food web are nonexistent. The development of strategies that maximize the likelihood that organic rotational-NT can be adopted successfully, and the benefits this adoption confers to soil food web dynamics, will likely revolutionize organic farming in dry regions globally.

One of the major obstacles preventing widespread adoption of rotational-NT among organic farmers in the US Great Plains and similar regions is inconsistent weed control provided by the vegetative mulch produced by killed cover crops. Screening of species as potential cover crops should continue since cover crops will remain an important component of organic rotational-NT systems. Integrated weed management approaches must be refined so that a suite of biological, cultural, and physical tactics can be bundled which provide effective and consistent control of annual and particularly perennial weeds in organic NT systems. Work is needed to develop strategies which optimize production of aboveground biomass by cover crops, as well as refine the technologies and practices which optimize termination of cover crops and production of a weed-suppressive vegetative mulch.

In many ways, organic rotational-NT is still in the development stage, much like where NT systems were in the 1970s in environments where synthetic fertilizers and pesticides are used. Progress since then largely explains why NT now is the dominant tillage system used on farms in a large portion of the US Great Plains. We suggest that continued research will result in similar progress being made in refining organic rotational-NT strategies such that economic and environmental sustainability can be optimized by adopting rotational-NT systems on organic farms.

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