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Review article

Effects of tillage systems on soil biodiversity

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ABSTRACT

Tillage affects the soil physical and chemical environment in which soil microorganisms live, thereby affecting their number, diversity and activity. Conservation tillage (CT) is practiced on 45 million ha world-wide, predominantly in North and South America but its uptake is also increasing in South Africa, Australia and other semi-arid areas of the world. It is primarily used as a means to protect soils from erosion and compaction, to conserve moisture and reduce production costs. In Europe, the area cultivated using minimum tillage is increasing primarily in an effort to reduce production costs, but also as a way of preventing soil erosion and retain soil moisture. Conservation tillage can improve soil structure and stability thereby facilitating better drainage and water holding capacity that reduces the extremes of waterlogging and drought. These improvements to soil structure also reduce the risk of runoff and pollution of surface waters with sediment, pesticides and nutrients. Reducing the intensity of soil cultivation lowers energy consumption and the emission of carbon dioxide, while carbon sequestration is raised though the increase in soil organic matter (SOM). Tillage-driven impacts on lumbricids and collembolans differed depending on soil texture, whereas those on nematodes and microbial communities varied depending on soil depth. Functional groups within certain taxa show differing tillage induced impacts. Linking several datasets on various indicator organisms clearly show that the decision on which tillage system should be applied must be taken for each individual case considering local soil characteristics.

1. Introduction

Tillage systems influence physical, chemical, and biological properties of soil and have a major impact on soil productivity and sustainability (Henle et al. 2008). In order to achieve the goal of safe productivity while protecting natural resources, plough less “conservation tillage” (CST) and “no tillage” (direct seeding, NT) management practices were developed in the USA, and initially applied in Germany in the 1950s (Pretty, 2008; Bäumer, 1970). CST is a system of raising crops with minimal mechanical soil disturbance while retaining crop residues on or near the soil surface (FAO, 2000). NT systems, in turn, are managed completely without soil tillage, with the only soil disturbance being caused by seeding and during harvest (Kassam et al. 2009). Compared to CVT, CST and NT provide numerous benefits by reversing the loss of organic matter (Holland, 2004); improving soil porosity, temperature and moisture (Stewart, 2007; Mazvimavi et al. 2008); biologically reducing the incidence of weeds, insect pests and diseases (Kassam et al. 2009); favoring biological nitrogen fixation (Huggins and Reganold, 2008); raising and stabilizing yields (Kassam et al. 2010); lowering production costs (Lahmar, 2010); protecting soils from erosion and compaction (Holland, 2004); and leading to reduced carbon emissions due to savings in machinery and energy use (Lahmar, 2010). However, shallow tillage makes weed control more difficult and often leads to an increased sensitivity of crops to pathogens and infections. Therefore, the adaptation, and mostly an enhancement, of herbicide and pesticide use is commonly required (FAO, 2000). Accordingly, such systems also have environmental drawbacks, usually relating to the fate of the agents used and potential contamination of other systems (Wardle, 1995). Nonetheless, plough less tillage is assumed to be biologically, ecologically and economically more efficient in producing required crop productivity. As soil biota and the processes they drive have large direct and indirect effects on crop growth and quality, soil and residue born pests, and the quality of nutrient cycling and water transfer, the conservation of their diversity has become a key component of a strategy towards agricultural sustainability (Giller et al. 2005). To develop cropping practices that ensure an optimal use and protection of soil biodiversity, the main challenge is to predict impacts of tillage systems on organisms and to understand the links between ecosystem processes and services, and the scale at which each member of soil biota contributes to their provision (Temme and Verburg, 2011; Roger et al. 2010). The principal differences between tillage systems involve cultivation, residue management and manipulation of weed levels (Wardle, 1995). Accordingly, properties and habitat conditions in soil, which drive and direct biodiversity below ground, differ as well. Abundance, biomass and activity of soil biota, in this context, are hypothesized to be mainly affected by amount, quality and distribution of organic matter as basic food source, soil structure and pore size distribution as available living and moving space, air and water movement as environmental milieu, and indirectly via changed interactions within the soil food web (Wardle, 1995). In line with this, the terms “tillage induced” and “tillage intensity” are related to the management differences of the whole tillage systems, as just described. However, as most studies have mainly been short-term, small scale and with limited coverage of taxonomic, functional or trophic levels (Bulte et al. 2005), long-term impacts of tillage systems on below ground biodiversity are only poorly understood. Moreover, potential interaction effects between tillage and distinctive ecosystem properties such as crop type as primary nutrient provider and soil texture as a structural habitat defining characteristic are only rarely analyzed. Thus, further integrating studies, combining several indicator organisms and respective relevant parameters are needed in order to assess the potential of tillage measures to maintain high soil biodiversity (Barrios, 2007). CST is generally less adopted and researched in Europe compared to other regions (Lahmar, 2010). So a survey on the scientific literature published during the past six decades was conducted to analyze the state of knowledge concerning the impact of CVT, CST and NT on soil biota. We concentrated on data from agro-ecosystems in Germany, considering a wide range of different soils representative for temperate regions. Soil biodiversity, in this context, is best considered by focusing on organisms that cover a broad range of functional groups and dimensional scales, thereby revealing numerous interaction effects and driving several ecosystem functions (Barrios, 2007).

2. Soil biodiversity

Cultivated soils are generally regarded as having a reduced biodiversity compared to uncultivated soils (Genckiser, 1997). Soils cultivated by CT may lie somewhere in between the two extremes (Kladivko, 2001), their position depending on other factors such as inputs of inorganic and organic fertilizer, pesticides and the crop rotation. The benefits of enhancing soil biodiversity have not been widely researched because productivity has been increased through the use of inorganic fertilizers, pesticides, plant breeding and soil tillage and liming. Most interest has been generated within lower input systems where the importance of a diverse and productive soil fauna has been recognized as being essential in the recycling of nutrients, improving soil structure and suppression of crop pests and diseases (Zaborski and Stinner, 1995). These include: (1) effects of tillage on soil organism populations, functions and interactions (Kladivko, 2001); (2) the function of soil fauna and processes that occur (Lavelle et al. 2006); (3) the impacts of tillage on detritus food webs (Wardle, 1995). The following sections review soil organisms and the implications of soil tillage; however, as studies on lower input systems have demonstrated, tillage cannot be examined alone as the maximum benefits are gained when CT forms part of an integrated approach to crop management (Holland, 2004). The levels of inorganic N inputs, pH and the levels and location of SOM within the soil profile determine soil stability, biodiversity and abundance. The higher level of SOM at the soil surface created using CT encourages a different range of organisms compared to a plough-based system in which residues are buried (Werner and Dindal, 1990). The soil fauna were divided into three groups by Lavelle (Lavelle et al. 2006):

1. Microfauna (e.g. bacteria, mycorrhizal fungi, protozoa, Nematode, Rotaroria and Tardigrada). They inhabit the soil solution and utilize organic compounds of low molecular weight.
2. Mesofauna (e.g. Collembola, Enchytraeidae, Acarina, Protura and Diplura). These live in the pore system and feed upon fungi, decomposed plant material and mineral particles, or are predatory.
3. Macrofauna (e.g. Gastropoda, Lumbricidae, Arachnida, Isopoda, Myriapoda, Diptera, Lepidoptera, Coleoptera). These reside between the soil micro-aggregates feeding upon the soil substrate, microflora and fauna, SOM and surface flora and fauna. They have the ability to move the soil and therefore affect soil porosity, water and air flow.

2.1. Microfauna

2.1.1. Nematode

According to the food specificity, species diversity and high abundance of nematodes in agricultural systems, investigations focusing on this microfauna group can be highly informative in the context of functional changes in arable soils (Freckman, 1989; Yeates and Bongers, 1999). Nematode populations are strongly influenced by the quality of organic amendments as they are adapted to a certain diet, and show clear preferences for specific food sources (Ruess et al. 200). Moreover, they need a certain degree of soil moisture as they depend on water films within the soil to move (Gaugler et al. 1993). Their abundance, activity and community structure, therefore, are highly correlated with soil biological, chemical and physical microsite properties, which change depending on tillage interventions (El Titi, 2003; Lenz and Eisenbeis, 2000). Thus different tillage systems might result in different nematode populations which, in turn, promote or inhibit specific processes and functions. To get insights in these changes, data on diversity indices which base on the principle that different nematode taxa have contrasting sensitivities to stress and, thus, indicate changing conditions in soils, represent a valuable tool (Gardi et al. 2009). Nonetheless, cultivation measures regulate nematode community structures as they reflect that several feeding types are differently affected by a reduction of tillage intensity, whereas bacterivorous, fungivorous and omnivorous species benefitted under CST, root-feeding species were favoured when NT was applied (Minton, 1986). Abundances of herbivores did not reflect any difference between CVT and CST, but tended to decrease under NT conditions. Unlike individual numbers of the other feeding groups, densities of carnivorous nematodes did not reflect any effect of soil tillage intensity. As these findings in their entirety did not exactly reflect any of the results on nematode feeding types described in other studies, this literature survey affirms the conclusion of Carter et al. (2009), Mc Sorley and Gallaher (1994), Lopez Fando and Bello (1995) and Holland (2002) that nematode responses to tillage intensity are highly variable and obviously depend on numerous other factors. However, in total, only individual numbers of root-feeders were significantly affected by soil tillage intensity. These organisms most probably profited from NT due to an increased duration of active roots and an increase in root length density, providing additional food availability. Fungivores and bacterivores, by contrast, tended to be more abundant under CST compared to NT (Lampurlanés et al. 2001). As microbial feeding nematodes are strongly linked to levels of bacterial and fungal biomass as their main food source, this finding again indicates the close relation of microorganisms to the distribution of organic matter in soil. Changes in abundances of bacterivorous and fungivorous nematodes, which in turn tend to be regulated by predatory nematodes (Wardle, 1995), indicate that trophic interactions play a major role in driving and directing influences of tillage related practises on soil biota. In conclusion, these results on nematodes indicate that NT systems are most stable, whereas CST systems have the potential to show a higher productivity due to increased energy and nutrient cycling.

2.2. Mesofauna

2.2.1. Collembola (springtails)

Collembolans represent an important mesofauna group in arable soils as they participate in decomposition processes, increase nutrient mobilization and catalyze microbial activity by grazing on bacteria and fungi (Kaneda and Kaneko, 2008). According to their functional diversity collembolan species can be classified to three life-form types on the basis of their vertical stratification in soil (Kasprzak, 1992): atmobiont (dwelling on the soil surface), hemiedaphic (living closely below the soil surface) and euedaphic (inhabiting deeper soil layers). Changes in collembolan community compositions and individual densities might have far-reaching consequences for microbial processes and, especially in agro ecosystems of utmost relevance, occurrence and reproduction of fungi and bacteria including potential pathogens. Against this background, collembolans show a great potential as bio indicators for the evaluation of changing soil conditions (Ehrnsberger et al. 1993; Parisi et al 2005). These mesofaunal organisms, hence, revealed a reverse effect compared to those on earthworm populations and benefitted under CVT but were not favoured by the improvements of soil structure due to tillage intensity reduction. The present findings, thus, contradict the results of Sabatini et al. (1997) and Petersen (2002) from Italian and Danish soils, who described collembolan abundances not to be affected by tillage intensity. Concerning interaction effects, collembolans, as well, indicated a significant impact of tillage intensity depending on soil texture. In this context, data on sandy, silty and loamy soils were available. When comparing abundances from CST to those from CVT systems, it becomes obvious that individual numbers rose in silty soils (47%), but decreased in sandy (10%) and loamy (35%) soils (Friebe et al. 1991; Frey et al 1999). To unveil the underlying changes in community composition and to detect potentially associated functional changes, the relative abundances of the three life-form types in silty and loamy soils, where tillage impacts were most pronounced, were analyzed (Carter et al. 2009). In silty soils, the relative abundances of all life-form types did not differ between CVT and CST. Linking this finding to the CST induced increase in absolute individual numbers of collembolans detected in silty soils, it can be concluded that all life-form types were equally promoted under CST in silty soils. In loamy soils, by contrast, the relative abundances of atmobiont, and, particularly, euedaphic species decreased under CST (atmobiont: 3%, euedaphic: 51%) compared to CVT (atmobiont: 10%, euedaphic: 65%) conditions (El Titi, 2003). Thus, the CST induced reduction in total collembolan density detected in these soils was due to a decline in individual numbers of these life-form types. Such effect has already been described by Moore et al. (2001) with regard to atmobiont species. Concerning the most strongly affected euedaphic species, the integrated analyses of occurring data indicate that organisms which depend on a far-reaching and connected web of soil pores, for instance, due to their restricted burrowing activity, were adversely affected by plough less tillage in soils of fine texture such as loam. Under such conditions, the loss of potential living space obviously overlays the positive effects exerted by CST (Sabatini et al. 1997). However, corresponding to the findings on earthworms, collembolans are, moreover, differently affected by soil tillage intensity depending on the particle size distribution characterizing their habitat in association with their ability or disability to burrow. The complexity of these interacting effects might be one possible reason for the inconsistency of described tillage-induced effects on collembolans (Wardle, 1995) which cover a vast range of potential impacts.

2.2.2. Acari (mites)

Mites account for a large number of individuals and species within the soil mesofauna and, depending on species, exhibit specific ecological demands (Karg et al. 1982). Densities of bacterivorous and fungivorous mites, for instance, show a strong correlation to microbial activity, whereas the species composition of carnivorous mites like Mesostigmata indicate the occurrence of prey organisms like nematodes, enchytraeids, collembolans or other mites (Karg, 1968). Moreover, mites show a high level of adaptation to their preferred habitats in soil (Karg and Freier, 1995). According to these characteristics mites represent valuable indicators in assessment of functional changes in soils (Karg, 1986). Whereas total individual numbers of mites were evenly distributed throughout the whole soil layer of 0e30 cm depth under CVT, they clearly decreased with increasing soil depth when CST was used. Thus, in the upper soil layer (0e5 cm) individual densities were higher under CST compared to CVT, whereas deeper in the soil (5e15 cm), the reverse was true. This result affirms the previous findings of Edwards and Lofty (1969), Wallwork (1976) and Price and Benham (1977) from the UK and the USA, and indicates that total mite densities were highest where the largest amount of organic matter was provided. It can be concluded that mites in total, like collembolans, were less sensitive to mechanical injury and soil inversion exerted by ploughing. Besides the publications that focus solely on total mite abundances (Gardi et al. 2009), some other studies describe tillage-induced impacts on individual numbers of certain mite orders (Derpsch et al. 2010). However, comparing the order-specific relative abundances under CVT and CST in sandy, loamy and silty soils, impacts contradictory to those detected by means of total individual densities were found (Hobbs, 2007). Although total mite abundances did not show any significant interaction effect between tillage and texture, clear differences became obvious when data on certain taxa were analyzed separately. In sandy soils all four orders (Astigmata, Prostigmata, Cryptostigmata and Mesostigmata) reflected a relative abundance of less than 30% under CVT, compared to over 70% under CST. In loamy soils the share of these orders varied between 37 and 45% under CVT, compared to between 55 and 63% under CST conditions. Only in silty soils did more than 50% of total Prostigmata and Cryptostigmata occur in CVT systems (Cheng et al. 1990). As studies on both total mite abundances and densities of certain orders comprise a broad range of crops, locations, and soil types, factors other than those named might be the driving force causing these contradictory findings. In this context, soil moisture conditions or tri-trophic effects, depending on the occurrence of predators or prey species, might represent parameters that have the potential to regulate mite populations independent of tillage intensity or texture. However, the proximate causes underlying this contradiction might not be identified at this point. Nonetheless, the integrating analysis of data on mite communities permits some general conclusions on tillage-induced impacts on these key organisms. Thus, it can be assumed that associated with a reduction in tillage intensity, the total number of mites decreased, while the community composition changed. Tillage effects on mites, thus, were taxon-specific as already indicated by Wardle (Wardle, 1995) and might, despite the lack of significant interaction effects of the whole community, in some cases, have differed depending on soil texture. According to this result, descriptive examples for the specificity of tillage effects depending on taxonomic level were exemplarily analyzed using taxa for which sufficient data exist (Basch et al. 2008; Day and Quinn, 1989). This detailed analysis shows that Gamasina (Mesostigmata), for instance, involves families that were differently affected by tillage intensity. Such specific responses of Gamasina might be of major agricultural importance and require further analyses of influencing factors, as Gamasina are assumed to control pest species of nematodes (such as Ditylenchus dipsaci and Heterodera avenae) and collembolans (Onychiurus armatus) (Holland, 2004).

2.2.3. Enchytraeidae (potworms)

Enchytraeids are of great importance in arable land as they exert a large influence on the soil structure, promote decomposition processes, accumulate nutrients in their casts and provide an equal horizontal distribution of nutrients throughout the soil (Hooper et al. 2005). Their impact on soil structure formation conforms to that of Lumbricidae, but on a smaller scale (Dawod and Fitz Patrick, 1993). Utmost relevance concerning future food and energy supply. Moreover, the data pool comprising other plants cultivated with NT is small, and their inclusion would reduce the validity of results. Enchytraeid abundances tended to be highest under CST, independent of crop and soil texture. The generally lowest individual numbers were detected in NT systems. As CST, representing the intermediate management system between CVT and NT, reflects the most beneficial effects, no general conclusions are possible on whether enchytraeid abundances decrease (Kasprzak, 1982) or increase (Graine, 2001) subsequent to cultivation. This finding illustrates that their vertical stratification in soils, first of all, depended on the availability of soil organic matter as the basic food source. By means of these data it gets obvious that enchytraeids were generally favoured by the mulch layer under CST, but, needed a certain amount of soil tillage as well. Under NT conditions their abundances decreased drastically, whereby their contribution to small-scale soil structure formation and nutrient distribution diminished. Thus, in contrast to earthworm-induced processes, the preservation of enchytraeid-driven processes depends on a minimum of soil loosening action (Lagerlöf et al. 1989).

2.3. Macrofauna

2.3.1. Lumbricidae (Earthworms)

Earthworms are of utmost relevance for the preservation of soil structure as they represent crucial ecosystem engineers (Lavelle et al. 2006) and important decomposers in soils. They are one of the most important macrofaunal groups in temperate regions and of great agricultural interest as they provide several benefits via the enhancement of soil aggregation (Shipitalo and Protz, 1989) and the penetration of plough pans, creating channels for drainage, aeration, and root growth (Joschko et al. 1989). According to their functional diversity, allowing the classification in three different ecological groups (anecic, endogeic, epigeic), they represent valuable indicators for detecting changes in soil conditions, functions and health (Doube and Schmidt, 1997). Total earthworm abundance, biomass, and species diversity were increased significantly in tillage systems with lower tillage intensity. The magnitudes of the increases were larger than those found by Jordan et al. [58] in the UK, but the general increase with decreasing tillage intensity has been found commonly in other countries and climates (Hangen et al 2002; Chan, 2001; Ivask et al. 2007). The interacting effects of reduced injuries, microclimate-changes, decreased exposure to predators at the soil surface, and an increased availability of organic matter providing a convenient food source (Zicsi, 1969; Larink and Schrader, 2000; Capowiez et al. 2009) are thought to drive the increase in earthworm biomass and abundance. According to the results of Holland (2004) and Pelosi et al. (2009), the present data analysis showed that the number of earthworm species and species diversity was increased in tillage systems with reduced tillage intensity. This dependence of tillage effects on the particle size distribution was even obvious within soils of a certain texture. Earthworm abundances in different kinds of silt, for instance, reflected a significantly increasing positive impact of reduced tillage intensity from loamy, via sandy to clayey silt (Karg and Freier, 1995). This finding illustrates the importance of integrating studies, combining several parameters and locations (Barrios, 2007), as single sites might not reflect the whole spread of possible impacts and changes. Thus, in order to obtain a healthy lumbricid population it is essential to consider the soil texture when making a decision on what kind of soil tillage should be used. Impacts of tillage intensity on the functional diversity of themacrofauna are indicated by changes in the community composition of ecological earthworm groups. Abundances of anecic and endogeic species, in this context, reflected a significant effect of tillage intensity, with both being most positively affected by NT treatment (Edwards and Lofty, 1969). Individual densities of epigeic earthworms, by contrast, did not significantly differ depending on tillage system. Comparing CVT and CST treatments, the data suggest that comparatively anecic species benefitted under CST, whereas individual numbers of endogeic species decreased. This finding indicates that organisms inhabiting the soil were differently affected depending on their vertical stratification in combination with body size (Kasprzak, 1982). Whereas the ploughing procedure represented the main factor adversely influencing larger anecic species via injuries and the disruption of pores, this aspect was of minor relevance for smaller endogeic species inhabiting deeper soil layers. The latter, in turn, profited more from soil inversion and loosening action, providing adequate aeration and sufficient food supply, than from the reduction of soil disturbance. Thus, the assumption that deep burrowing earthworms might have the potential to escape the zone of disturbance (Reinecke and Visser, 1980) was verified for endogeic species. However, in total, NT represented the management system that provided the most favourable conditions for earthworms and, thus, ensured and optimized earthworm driven processes at most. This finding is affirmed by the tendency of increasing species numbers and enhanced biomasses detected for all ecological groups as a consequence of direct seeding (Kassam et al. 2005).

3. Conclusion

This literature survey reveals that a more usual application of CST and NT might help reaching biodiversity conservation, which is essential to ensure agricultural sustainability. However, tillage intensity reduction does not represent a universal solution since its successful application strongly depends on the soil conditions. Thus, to ideally manage soil biodiversity while reaching optimal soil health and sufficient production capacity, respective local conditions like soil texture have to be considered when developing and selecting optimal tillage systems.

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