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Do tillage systems influence nitrogen fixation in legumes? A review

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ABSTRACT

Adopting conservation tillage practices such as zero tillage can enhance soil quality, compared with conventional tillage practices that disrupt soil structure. The benefits of maintaining soil structure through no tillage typically result in improved biological processes and increased microbial biodiversity. Rhizobia are considered here as an indicator for soil quality, as they are ubiquitous, present in high populations in many soils, rapidly respond to soil changes, and are crucial for legume productivity. The process of symbiotic nitrogen fixation, whereby rhizobia form a symbiotic association with leguminous plants and fix atmospheric nitrogen gas, can substantially improve agricultural system as, it has how environmental and economic costs for nitrogen supply. Tillage methods affect many soil characteristics such as aeration, structure, temperature and water use, all of which affect the microbial composition, nitrogen fixation and nodulation. This review systematically summarizes the effect of tillage systems such as conventional tillage and minimum tillage systems on nitrogen fixation by legumes. We identify that conservation tillage typically enhances nodulation and nitrogen fixation, through increased soil moisture retention and soil temperature, and increased soil microbial biomass. However, conservation tillage can lead to a reduction in soil pH and increased soil compaction, which can reduce nodulation.

1. Introduction

Soil cultivation is a fundamental agronomic practice affecting soil and crop properties. The key object for cultivating the soil is to create an appropriate environment for the germination of seeds, the establishment of seedlings and to allow the optimal yields of crops (Vetsch and Randall, 2002). Accordingly, different kinds of tillage methods are used on farms in preparation for planting crops. The most common techniques of soil tillage are conventional tillage (CT), reduced tillage (RT) and no-tillage (NT). Often, RT and NT are used as a component of conservation agriculture, in which reduced tillage is used in concert with retaining stubble and employing a rotation of crops (FAO, 2008), although these components are not universally adopted by farmers (Giller et al., 2009). We group these three tillage types here as conservation tillage.. CT practices typically leave less than 15% residue on the surface, while conservation tillage practices often leave more than 30% of residue as a soil cover at the time of planting of the next crop (CTIC, 2015). NT direct seeding 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. NT is the conservation tillage system that retains the greatest amounts of crop residue (CR) on the soil surface, and the benefits are most pronounced in dry regions following adoption of NT, where the soil water conservation that occurs is a particular advantage (Carr et al., 2006). Conservation tillage makes an appropriate 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 (OECD, 2013). Changes in soil conditions associated with conservation tillage intensity and increased CR retention include increased soil organic carbon (Lal, 2004), improved surface physical conditions and plant nutrient status (Follett and Peterson, 1988; Arshad et al., 1999), and enhanced microbial biomass and activity (Doran, 1980; Frey et al., 1999).

The Leguminosae (legume family) consists of about 18,000 species. Although only small numbers of leguminous species are used as crops and pastures, they are very important food and feed crops worldwide (Herridge et al., 2008). The use of legumes can provide an option for reducing a heavy reliance on nitrogen fertilizers to sustain crop production. Legumes are unique in agriculturally grown crops and pastures in that they have the ability to form a symbiotic relationship with soil

Abbreviations: BNF, biological nitrogen fixation; CT, conventional tillage; CR, crop residue; Ndfa, plant N derived from atmospheric N2; NT, no-tillage; RT, reduced tillage

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bacteria collectively called rhizobia (Poole et al., 2018). The bacteria are housed in special root organs called nodules where they fix atmospheric nitrogen gas (N_2) to ammonia (NH_3), which the plant can assimilate via glutamine synthase to form glutamine (Poole et al., 2018). In return, the bacteria derive plant carbohydrates, mainly from malate as a carbon and energy source that fuels biological nitrogen fixation (BNF) (Hu et al., 2007). However, nodule formation and BNF are very sensitive to deleterious environmental conditions.

Altered chemical and physical properties of soil that are influenced by different tillage methods can affect factors directly related to soil biotic activities, such as soil humidity, organic matter, ventilation and temperature, as well as the extent of interaction between soil organic matter and minerals. A review by Martens (2001) has reported greater microbial abundance under NT soils with a more favorable microclimate compared with soils under CT. Moreover, NT often results in increased soil water content (Lafond et al., 1992), and this reduced water stress may increase BNF in grain legumes (Bennet and Albretch, 1984). NT soils often have less soil nitrate compared with cultivated soils (Doran, 1980), which may affect BNF, as nodulation and N_2 fixation in legume crops is increased in soils with low concentration of nitrate (Cowie et al., 1990). In contrast, increased soil nitrate under CT decreased BNF (Cowie et al., 1990). Hughes and Herridge (1989) found that reduced amounts of soil nitrate in a NT soil increased soybean nodulation and BNF. For cool seasons grain legumes under NT, the combined effects of lower nitrate and reduced water stress may increase BNF. There is a need to quantify any increased N_2 fixation associated with NT and to gain an understanding of the mechanisms involved. On the other hand, some contradictory results have been reported by other researchers. Roper et al. (1994) indicated that cultivation encouraged nitrogenase activity by free-living N_2 fixing bacteria compared with the NT treatments, althoughtotal inputs from these systems are known to be < 10 kg N/ha (Unkovich and Baldock, 2008). Plant N derived from atmospheric N_2 (%Ndfa) and the amount of N_2 fixed did not vary in faba bean under the effect of NT or CT systems, likely due to the negligible difference in soil NO_3^-–N content between the two systems (Lopez-Bellido et al., 2006). According to a study in Alberta, tillage systems including NT and CT did not influence N_2 fixation rates of field pea (Izaurralde et al., 1995). Neumann et al. (2007) reported that N_2 fixation and the competitive ability of intercropped pea (*Pisum sativum* L.) were higher under CT than under minimum tillage. As the differences between the tillage systems were not driven by soil N supply and soil N uptake, other soil parameters such as bulk density may have led to a lower competitive ability and decreased the N_2 fixation of intercropped pea in the mixture under minimum tillage compared with the CT.

We believe that research related to tillage systems and the agronomic mechanisms that influence N_2 fixation of legumes is essential to define, as BNF has a critical role across different farm scales and in conventional and organic agriculture. Moreover, soil nitrogen is one of the most common yield-limiting elements for crop growth and N fixation has the capacity to reduce N applications, increase soil quality and reduce global N losses. To date, relatively little is known about the effects of tillage on rhizobacterial activity in legumes. Therefore, in the present review an attempt is made to shed light on the direct and indirect role that tillage systems play on BNF in legumes.

2. Response of BNF to tillage

Generally, the extent of N_2 fixed by grain legumes is affected by rainfall and temperature (Streeter, 2003), the abundance of soil rhizobia (Mabood et al., 2006; Denton et al., 2013) and by their interaction with other biological, physical and chemical properties of the soil (Rebafka et al., 1993; Giller and Cadisch, 1995; Goss and de Varennes,2002; Farhangi-Abriz and Torabian, 2018). Soil moisture content, temperature, mineral nitrogen content, size of the rhizobial population and soil pH are soil characteristics that can affect N_2 fixation (Fig. 1) (Hungria and Vargas, 2000).

These factors are themselves are influenced by management practices such as tillage and CR application. Soil tillage methods have complex effects on physical, chemical and biological properties of soil, which alter the biological properties of soil. These changes are the indirect results of tillage. Tillage is among the major practices that influence organic matter of soil; the soil organic matter changes the physical, biological and chemical properties of the soil environment and subsequently affects N_2 fixation (Kihara et al., 2012). The positive effects of NT enhance soil quality by decreasing soil bulk density, reducing soil temperature and increasing soil moisture, enhancing microbial activity, improving soil structure, and increasing soil organic content (Benitio, 2010; Jina et al., 2011; Aziz et al., 2013). The potential of the NT system for increasing N_2 fixation in grain legumes is largely achieved through a decrease in available N, increased water content and improved soil physical properties, as reported by Van Kessel and Hartley (2000); Reiter et al. (2002) and Souza et al. (2003). In a study by Mulas et al. (2015) which was carried out under different environments and tillage systems, BNF of common bean in CT was higher than NT. N_2 fixation and dry matter yields in soybean were found to be greater under NT than under CT (Herridge and Bergersen, 1988). Overall, NT systems generally increased nodulation, the percentage of Ndfa (plant N derived from atmospheric N_2) and total amount of N fixation and grain yield, in comparison with CT, as indicated in Table 1.

NT systems promoted nodulation of vetch plants to a higher degree than rotary hoeing and ploughing followed by one rotary hoeing (Sidiras et al., 1999). The quantity of N fixed by soybean under NT practice exceeded CT (Omondi et al., 2014). Nodule sizes in peanut (*Arachis hypogaea* L.) were larger under conservation tillage treatments than nodules in CT (Rowland et al., 2015). In work from Dogan et al. (2012), the effects of six different tillage methods including CT with residue, CT with burnt residue, RT with heavy disking, RT with rotary tiller, NT with heavy disking and NT with direct seeding were studied in relation to nodulation of soybean. CT negatively affected number of nodules and plant nitrogen contents. CT in some cases can increase the nitrogen uptake by legumes; however, this response is highly dependent on the plant species (Lopez-Bellido et al., 2011a) (Fig. 2). Higher N_2 fixation parameters in two RT treatments (RT with heavy disking and reduced tillage with rotary tiller) were seen compared with the other applications. According to Van Kessel and Hartley (2000), conservation agriculture and NT management practices will, therefore, lead to a stimulation of N_2 fixation, at least until a new equilibrium between residue input and the rate of decomposition is reached.

Higher amounts and percentages of Ndfa have been observed in the grain of pea under a NT system compared with CT within a 4-year rotation experiment (Matus et al., 1997). However, Jensen (1998) found no difference in the Ndfa of pea shoots from a small plot experiment with simulated tillage treatments. Tillage system did not affect %Ndfa in chickpea and faba bean. Moreover, N_2 fixed as the amount per unit area of chickpea, faba bean, lentil and pea did not change under CT and NT (Ruisi et al., 2012). The percentage of nitrogen derived from atmosphere in different legume plants such as lentil, pea, faba bean, soybean, chickpea and mung bean under different tillage methods is presented in Fig. 3. Rupela and Saxena (1987) maintained that straw mulch can indirectly affect nodulation and N_2 fixation by affecting the soil's physical, chemical and biological environment, although Horn et al. (1996) indicated that N_2 fixation was not significantly affected by the tillage system. Accordingly, in an experiment with chickpeas, Doughton et al. (1993) did not find any influence of tillage on N_2 fixation. Two varieties of soybean fixed a substantial amounts of N under both CT and NT systems; the %Ndfa was similar between tillage systems, but the kg N fixed was higher under the NT tillage system (Rennie et al., 1988). On the other hand, adverse effects of CR retention on nodulation and N_2 fixation of legumes have also been reported for groundnut (Rebafka et al., 1993), although these