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Weed and insect management alter soil arthropod densities, soil nutrient availability, plant productivity, and aphid densities in an annual legume cropping system

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ABSTRACT

Transgenic glyphosate-resistant (GR) soybean (*Glycine* max L. Merr.) is cultivated throughout the United States. Soybean growth is influenced by the presence of weeds, although managing non-crop vegetation can potentially impact soil arthropods, which are being increasingly recognized for their impacts on soil health, plant growth, and above-ground trophic interactions. We investigated how weed management (weedy controls, hand-weeded, glyphosate herbicide) and soil insecticide (chlorpyrifos) application affected densities of soil arthropods, soil nutrient availability, soybean growth and yield, and densities of an above-ground herbivore on sandy and clayey soils for two consecutive growing seasons. The soil insecticide treatment was intended to lower densities of subterranean arthropods to gain insight into how their presence influenced other factors, although their densities were primarily reduced the first year of the study. Surprisingly, weed management and soil insecticide use had virtually no interactive effects on any response. Weed presence had a positive effect on soil K at the sandy site and on nodule density per unit root. Negative effects of weed management on plant growth and aphids were related to the presence of weeds rather than herbicide use. Reduced soybean aphid density (at the clayey site) and soil P availability (at the sandy site) were associated with insecticide treated plots. Conversely, several measures of plant productivity, including number of nodules per unit root, and root and shoot biomass increased in +insecticide plots compared to other treatments, although effect strength depended on year and location. Collembola were the dominant soil microarthropod, and their densities in 2012 were negatively associated with nodule numbers in 2013. One explanatory hypothesis is that increased plant growth in plots treated with insecticide was caused by altered soil arthropod-microorganism interactions, possibly affecting arbuscular mycorrhizae function. This work highlights the importance of management decisions that affect soil arthropods in annual legume production systems.

1. Introduction

The role of soil microarthropods in plant production and soil health is being increasingly recognized (Brussaard et al., 2007; Ferris and Tuomisto, 2015; Bender et al., 2016). Although some directly affect plants via root consumption (Hopkin, 1997; Endlweber et al., 2009), many affect plants indirectly via brown food webs or by influencing organic matter decomposition and nutrient cycling (Petersen and Luxton, 1982; Seastedt, 1984; Moore et al., 1988; Neher and Barbercheck, 1998), or via the presence of their cadavers (Kos et al., 2017). Soil arthropods may be especially important in legume crops, like soybean, that depend on symbiotic bacteria to fix nitrogen (Lussenhop, 1996). Soil microarthropods can also impact foliar herbivores (Scheu et al., 1999; Schütz et al., 2008; Megías and Müller, 2010) and their natural enemies (Scheu, 2001; A'Bear et al., 2014).

Collembola (springtails, Arthropoda: Entognatha) and mites (Arachnida: Acari) are among the most abundant soil microarthropods (Seastedt, 1984; Norton, 1990; Hopkin, 1997). Collembola are found world-wide and primarily feed on fungi or decaying plant material (Hopkin, 1997; Rusek, 1998). Some taxa are thought to consume arbuscular mycorrhizal fungi symbiotically associated with plant roots (Warnock et al., 1982; Jonas et al., 2007; Caravaca and Ruess, 2014), potentially disrupting uptake of key nutrients, especially phosphorus, that are critical for plant growth and legume productivity (Keyser and

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Li, 1992; O'Hara, 2001). Most oribatid mite (Acari: Oribatida) taxa feed on microbes and decaying plant material (Norton, 1990; Coleman et al., 2004). Ecologically, oribatid mites regulate organic matter decomposition and nutrient cycling, and influence soil structure (Behan-Pelletier, 1999; Coleman et al., 2004). To maximize agricultural production, we need to understand more about how soil arthropods affect crops, and how human activities, such as pest management practices, alter belowground processes.

Weeds are common pests within agricultural systems. Although weeds compete with crops for nutrients, water and sunlight, they represent a source of vegetative biodiversity (Altieri, 1999). Soil arthropods can be influenced by plants and vice versa (De Deyn et al., 2004; Bennett, 2010), and arthropod densities are often greater in weedy than weed-free environments (Altieri et al., 1985; Wardle, 1995). Weeds modify environmental conditions within the canopy and near the soil surface, including regulating temperature, increasing humidity, and decreasing wind (Norris and Kogan, 2005). Weeds often have large root profiles (Davis et al., 1967) with active rhizospheres within which soil arthropods are associated (Curry and Ganley, 1977; House, 1989; Garrett et al., 2001), provide food resources in the form of seeds (Brust and House, 1988; Bohan et al., 2011; Kulkarni et al., 2015), and contribute residue that impacts the detritus food web (Curry, 1973; Wardle, 1995; Wardle et al., 1999). Consequently, removal of weeds may cause either direct or indirect trophic effects on soil arthropods.

Herbicides are the primary weed management tool used within most agricultural systems. Glyphosate-resistant soybeans are used extensively in the United States (Cerdeira and Duke, 2006; Bonny, 2008), with 85 percent of total soybean production in 2013 relying on a glyphosate-based weed management system (NASS, 2014). The success of this technology has led to increased reliance on the herbicide glyphosate for weed management within soybean fields (Bonny, 2008). Glyphosate is a glycine derivative, and is a non-selective herbicide that kills plants by inhibiting the enzyme 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSP) within the shikimate pathway, thus reducing biosynthesis of aromatic amino acids within plants (Franz et al., 1997; Duke and Powles, 2008). Glyphosate is a widely used agrochemical for many reasons, including its low ecotoxicological risk (Baylis, 2000; Giesy et al., 2000; Duke and Powles, 2008). The general consensus is that glyphosate has little impact on non-target organisms, in part because it binds to soil, is rapidly degraded by microbes (Giesy et al., 2000; Haney et al., 2000; Borggaard and Gimsing, 2008; Duke and Powles, 2008), and only plants and microorganisms have a shikimate pathway (Herrmann and Weaver, 1999).

However, potential ecological impacts of glyphosate, including leaching (Vereecken, 2005) and effects on soil organisms and crop plants (Helander et al., 2012) may be worth considering. Research has suggested glyphosate negatively affects densities of beneficial soil microorganisms (Zaller et al., 2014; Druille et al., 2016) and affects the composition of the rhizosphere microorganism community (Kremer and Means, 2009), although others did not find strong effects (Liphadzi et al., 2005; Weaver et al., 2007; Barriuso and Mellado, 2012; Lane et al., 2012a,b; Nakatani et al., 2014). Several studies have found glyphosate negatively impacts legume nodulation, nodule biomass, or N-fixation (Mallik and Tesfai, 1985; Reddy and Zablotowicz, 2003; Zablotowicz and Reddy, 2004; Bohm et al., 2009; Kremer and Means, 2009; Zobiole et al., 2012), reduced plant uptake or tissue concentrations of micronutrients (Eker et al., 2006; Neumann et al., 2006; Cakmak et al., 2009), lower plant growth or biomass (Bott et al., 2008; Zobiole et al., 2010a), and altered seed composition (Zobiole et al., 2010b), although see Duke et al. (2012a,b). Regarding soil microarthropods, effects of glyphosate are thought to primarily be indirect via reduced plant cover (Brust, 1990; Wardle, 1995; Bitzer et al., 2002; Cerdeira and Duke, 2006), but Evans et al. (2010) found this herbicide altered the mobility and long-term survival of epigeal predatory arthropods.

We studied how weed management (herbicide, hand-weeding, weedy control) and using a soil insecticide to manipulate soil arthropods (natural level, suppressed) affected soil nutrients, growth of glyphosate-resistant soybean, and densities of an above-ground herbivore under sandy (coarse-textured) and clayey (fine-textured) soils for two consecutive growing seasons. We established the field study in two disparate soil contexts because soil structure and abiotic properties can impact the abundance, diversity, and behavior of soil organisms (Villani and Wright, 1990; Lauber et al., 2008; Birkhofer et al., 2012) and plant growth (Gliński and Lipiec, 1990; Passioura, 1991). We incorporated a hand-weeding treatment to separate effects of the herbicide from the presence/absence of weeds and used a broad-spectrum soil insecticide to suppress soil arthropod populations. Our hypotheses were that glyphosate application would (1) reduce soil nutrient availability, (2) negatively impact densities of soil arthropods, and (3) increase soybean growth and yield via weed suppression. Furthermore, we hypothesized that using a soil insecticide to reduce soil arthropod densities would have a negative impact on soybean growth and yield.

2. Methods

2.1. Experimental sites

On-farm field experiments were conducted during the 2012 and 2013 growing seasons at two sites located at a distance approximately 40 km from each other, but with differing soil textures. The soil at the first site ('Sandy') was a sandy loam (Leonard, North Dakota) in the Glyndon soil series (coarse-silty, mixed superactive, frigid Aeric Calciaquoll; Table 1). The soil at the second site ('Clayey') was a silty clay loam (Mapleton, North Dakota) with a mixed Dovray (fine, smectitic, frigid Cumulic Vertic Epiaquolls) and Bearden soil series (fine-silty, mixed, superactive, frigid Aeric Calciaquoll; Table 1).

2.2. Experimental design

The field experiment was laid out in a randomized complete block design with six replications. Each plot was 9.15 m by 9.15 m with 6.1 m alleyways between each plot. During both years on May 15, field plots were prepared for planting using a John Deere cultivator (wide field cultivator, spring tooth harrow, 2.3 m wide). Soybean variety Roughrider Genetics 607 Roundup Ready® (Monsanto Company, St. Louis, Missouri) was planted using a John Deere 71 flex planter with 76.2 cm between rows and twelve rows per plot at approximately 370,600 seeds per hectare resulting in a within row spacing of approximately 3.0 cm. In 2012 the sites were planted on May 22, whereas

Table 1
Location, basic soil properties, and rainfall at the two experiment sites.

	Sandy (Leonard)	Clayey (Mapleton)
Coordinates	46°39′58.3560″, −097°14′32.9640″	46°55′42.1680″, −097°01′03.1800″
Sand (g kg^{-1})	640	60
Silt (g kg^{-1})	240	560
Clay (g kg^{-1})	120	380
Texture	Sandy loam	Silty clay loam
Soil pH	5.8	7.3
EC (ds m^{-1})	0.57	1.19
Rainfall (cm)	Sandy (Leonard)	Clayey (Prosper[†])
May 2012	4.27	4.62
July 2012	11.15	1.63
May-August 2012	24.05	15.27
May 2013	7.75	10.52
July 2013	2.77	2.01
May-August 2013	27.10	36.8

[†] Rainfall data from weather stations in the North Dakota Agricultural Weather Network; Prosper was the closest to the Mapleton field site.