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Multivariate relationships influencing crop yields during the transition to organic management

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ABSTRACT

Crop yields are influenced by multiple, interacting factors, making it challenging to determine how specific management practices and crop rotations affect agroecosystem productivity. This is especially true in cropping systems experiments in which multiple management practices differ between experimental cropping system treatments. We conducted a cropping systems experiment in central Pennsylvania, USA, to analyze the effects of initial cover crop and tillage intensity on feed grain and forage crop productivity during the transition to organic production. We hypothesized that treatment effects of (1) tillage intensity (full or reduced); and (2) initial cover crops (annual rye (*Secale cereale*) or timothy/clover (*Phleum pratense/Trifolium pratense*)) on grain crop yield in a 3-year cover crop/soybean (*Glycine max*)/corn (*Zea mays*) rotation would be mediated by key agroecosystem function indicators (soil quality, weed pressure, and predatory arthropod activity). We used structural equation modeling (SEM) to attribute yield variation to treatment effects and abiotic factors as mediated by these ecosystem functions. We found that tillage intensity had both direct and indirect effects on corn yields. Full tillage had a direct, positive effect on corn yields, a negative effect on perennial weed density, and negative effect on a soil quality indicator (labile soil carbon). Full tillage also had an indirect effect on corn yields as mediated by perennial weed density. The initial cover crop influenced predatory arthropod activity-density and perennial weeds in year 2 (soybean phase), but had no effects in year 3 (corn phase). Abiotic and site factors influenced crop yields and other ecosystem functions in both rotation years. Our results highlight the utility of analytical approaches that consider the relationships among agroecosystem components. Through the analysis of management effects on multiple ecosystem functions, our results indicate that managing weed populations through tillage in organic systems can have the strongest effect on crop yields, although short-term profit gains may be at the expense of long-term loss in soil quality and beneficial insect conservation.

1. Introduction

Agricultural management practices influence a suite of interacting ecosystem functions, including food production, nutrient cycling, water retention, and pest regulation. In addition, farmers rarely change single management practices, but rather combine multiple management practices into management systems, such as no-till or organic production systems. Cropping systems studies in which multiple practices differ between experimental cropping system treatments have contributed to our understanding of how management systems influence agroecosystem productivity and environmental impacts (Drinkwater, 2002). However, results from systems-based studies have primarily been evaluated using statistical approaches that separately analyze management effects on individual functions, such as soil quality, nutrient cycling, weed dynamics, and productivity (e.g., Drinkwater et al., 1998; Fortuna et al., 2003; Davis et al., 2005; Grandy et al., 2006).

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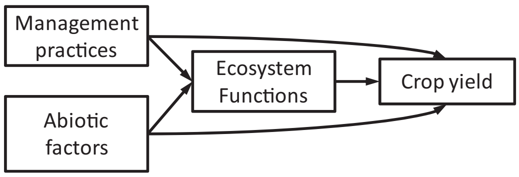

Fig. 1. Conceptual framework illustrating how management practices and abiotic factors can influence crop yield directly and indirectly through effects on mediating ecosystem functions.

More recently, the multifunctionality of cropping systems has been analyzed using multivariate statistical methods, including multiple regression (Cavigelli et al., 2008), principal components analysis (Clark et al., 1999), and discriminant analysis (Gosme et al., 2012). In addition, system multifunctionality has been represented visually using radar plots (Mäder et al., 2002) and the cumulative effects of management systems on multiple response variables have been evaluated through the use of semi-quantitative sustainability indices (Castoldi and Bechini, 2010). We still lack an understanding, however, of how management practices influence the relationships among multiple ecosystem processes or functions within cropping systems (Robertson and Swinton, 2005). For example, management practices and abiotic factors may influence crop yields directly or indirectly via mediating ecosystem functions, the ecological processes regulating the flux of materials and energy (Fig. 1). Understanding how ecosystem functions interact is particularly important for elucidating the mechanisms behind observed emergent effects of management practices. For example, shifting from a continuous corn rotation to a corn-soybean rotation improves nitrogen (N) availability to the succeeding corn crop that exceeds estimates of N inputs from soybeans (Karlen et al., 1991). This "rotation effect" is likely influenced by multiple interacting factors, including changes in labile soil carbon (C) inputs, microbial communities, and soil moisture dynamics (Gentry et al., 2013). Similarly, cover crops and tillage often have substantial impacts on weeds and crop yields (Liebman and Davis, 2000; Teasdale et al., 2007), but some of the underlying mechanisms remain unclear.

Structural equation modeling (SEM) is well-suited to analyze the structure of multivariate relationships that lead to the emergent properties of cropping systems (Grace, 2006). SEM allows researchers to propose an *a priori* model of structural relationships that include direct and indirect causal pathways. It is similar to a least-squares regression approach and has a history of use in the fields of biology, economics, psychology and sociology (Grace, 2006). More recently, SEM has been applied to studies in ecology (e.g., Grace et al., 2010; Sutton-Grier et al., 2010) and, to a lesser extent, agronomy (e.g., Davis and Raghu, 2010; Lamb et al., 2011), to test whether experimental data fit our conceptual models of ecosystem structure developed through prior experience and knowledge.

Managing tillage intensity to balance soil quality and pest control goals in organic production systems can be challenging. Building or maintaining soil organic matter is a cornerstone of organic production systems (Gliessman, 2007) due to the effects of organic matter on multiple functions, including nutrient cycling and pest and disease regulation (Zehnder et al., 2007; Drinkwater et al., 2008). Examples of management practices that can increase soil organic matter (SOM) include the use of cover crops, application of compost and manure, or reduction of tillage (Kuo et al., 1997; Drinkwater et al., 1998; Franzluebbers, 1999). However, weed management in organic systems typically relies on deep and/or frequent tillage and cultivation that depletes soil organic matter and has negative impacts on soil quality (Franzluebbers, 1999; Grandy and Robertson, 2007). In addition, tillage and the lack of living plant cover following tillage can have negative impacts on soil-dwelling predatory insect communities important for pest regulation in organic systems (Zehnder et al., 2007; Landis et al., 2000; Jonsson et al., 2008).

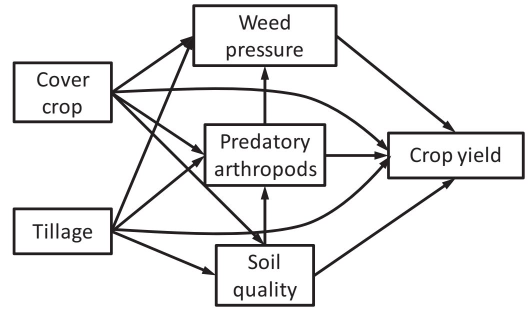

Fig. 2. Initial hypothesized model of how cover crop and tillage practices may affect crop productivity directly and indirectly through effects on soil quality, weed dynamics, and soil-dwelling predatory arthropod community dynamics.

The use of cover crops is another key component of organic production systems. Cover crops may help mitigate the negative effects of tillage in organic cropping systems by building soil organic matter, providing habitat for beneficial insects and suppressing weeds. Cover crops can provide important overwintering habitat for predatory arthropods, thereby promoting biocontrol of pest arthropods and increased weed seed predation (Gallandt et al., 2005; Lundgren and Fergen, 2011). Cover crop species differ in the functions they provide, such as pest control, erosion protection, and nutrient management. For example, annual cover crop species tend to have faster growth rates than perennials (Garnier, 1992), which can contribute to improved weed suppression. Perennial crop species tend to have a higher root:shoot ratios and root biomass is a key contributor to SOM stabilization and retention (Glover et al., 2010).

We conducted a cropping systems experiment to analyze the effects of initial cover crop and tillage intensity on soil quality, weed dynamics, and crop yields during the transition to organic production in a feed and forage production system in central Pennsylvania, USA. We focused on the transition period from conventional production to organic certification because the potential for reduced crop yields during this 3-year period is a constraint to the adoption of organic production practices (Pimentel et al., 2005). We hypothesized management practice effects on yield would be mediated by soil quality, weed populations, and predatory arthropods (Fig. 2). We used SEM to attribute yield variation to treatment effects as mediated by these three drivers of ecosystem function.

Some of the paths in our hypothesized model (Fig. 2) have extensive support in the existing literature, such as the effects of tillage on weed populations and the effects of weed populations on crop yields (Mirsky et al., 2012). Other relationships, however, are less well understood either because they have received little attention or they are thought not to be as important relative to other drivers. For example, tillage and cover crops can influence predatory arthropods, but there are few studies that examine how predatory arthropod activity-density directly influences crop yields (Letourneau and Bothwell, 2008; Letourneau et al., 2009). Complex trophic interactions may connect management effects on labile soil C to decomposer communities and predatory arthropod food webs that can influence weed seed predation and herbivore pressure on weeds and crops (Halaj and Wise, 2001). In addition, while it is widely assumed that organic matter quality and quantity affects crop yields, it is difficult to determine the importance of soil organic matter relative to other factors (Cassman, 1999). Our goal was to understand the relative importance of these different potential direct and indirect drivers of ecosystem functions within a cropping system and to identify potential management practices