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Managing the trade off between nitrogen supply and retention with cover crop mixtures

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ABSTRACT

The ability of cover crop mixtures to provide both nitrogen (N) retention and N supply services has been extensively studied in research station experiments, especially with grass-legume bicultures. Mixtures are often as effective as grass monocultures at N retention, but the N supply service can be compromised when non-legumes dilute the presence of legumes in a cover crop stand. To study the tradeoffs between N retention and supply when using cover crop mixtures, we measured N retention and supply in distributed on-farm experiments, developed multiple linear regression models to predict N retention and supply based on cover crop functional characteristics and environmental variables, and synthesized the regression models into a graphical analysis tool. The experiments took place on three organic farms and a research station in Pennsylvania, USA and tested 3-species and 4-species cover crop mixtures in comparison to commonly used grass and legume monocultures. Cover crop treatments were planted between a small grain crop harvested in mid-summer and a maize (*Zea mays* L.) crop planted the following spring. Potential nitrate (NO_3^-) leaching below 30 cm, an indicator of the N retention service, declined as the presence of non-legume species in a cover crop increased (r^2 = 0.72). Potential NO_3^- leaching increased as the August soil NO_3^--N concentration increased and as the fall biomass N content of winter-killed species or canola (*Brassica napus* L. 'Wichita') increased. Relative maize yield, an indicator of the N supply service, decreased as fall and spring cover crop biomass carbon-to-nitrogen (C:N) ratios increased and increased as total spring biomass N content and soil carbon (C) concentration increased (r^2 = 0.56). Synthesizing the regression models in a graphical analysis tool revealed a tradeoff between N supply and retention services for cover crop mixtures, where increasing the fractional non-legume seeding rate to reduce potential NO_3^- leaching also reduced relative maize yield. The tradeoff could be minimized by managing environmental conditions and cover crop composition so that potential NO_3^- leaching remains low even when the fractional non-legume seeding rate is low. The regression models suggest this could be achieved by maintaining low soil NO_3^--N concentrations prior to cover crop planting in August, not including winter-killed legumes in the mixture, and using non-legume species that are the most efficient at N retention. Thus, with thoughtful management of cover crops and soils, farmers may be able to realize the potential of cover crop mixtures to provide high levels of both N retention and supply services.

1. Introduction

Replacing synthetic fertilizer inputs with biologically supplied nitrogen (N) sources and minimizing N losses to the environment are both important goals for farming systems that rely on ecological nutrient management, including organic cropping

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systems (Drinkwater et al., 2011; Drinkwater and Snapp, 2007). In organic systems, cover crops can supply N to subsequent crops and retain nitrate (NO_3^-) against leaching (Thorup-Kristensen et al., 2012). However, individual cover crop species can often provide optimal levels of only one or the other of these services (Ramírez-García et al., 2015; Wagger et al., 1998) due to differences in N acquisition strategies and tissue chemistry between cover crop types such as legumes and grasses. One cover cropping strategy with the potential to optimize both N supply and N retention services is to plant a mixture of cover crop species, however inherent tradeoffs between N supply and retention may pose a challenge to realizing both services from a cover crop.

Bicultures of grass and legume cover crops are often able to reduce NO_3^- leaching to similar levels as grass monocultures (Sainju et al., 2007; Bergkvist et al., 2011; Tosti et al., 2014; but see Ranells and Wagger, 1997). However, the N supply from cover crop bicultures to subsequent crops has a high level of variability across studies (Miguez and Bollero, 2005) and is often less than the N supply from a legume monoculture (Benincasa et al., 2010; Clark et al., 2007a, 1994; Miguez and Bollero, 2005; Tosti et al., 2012). In addition to cover crop bicultures, cover crop mixtures composed of more than two species have been tested with the goal of enhancing the overall level and diversity of services provided by a cover crop (Creamer et al., 1997; Smith et al., 2014). However, the provisioning of both N retention and N supply services by higher diversity cover crop mixtures has only been evaluated by one study (Finney et al., 2016) and information to guide the management of higher diversity cover crop mixtures to provide both N retention and N supply services is lacking.

Cover crop residue carbon to nitrogen (C:N) ratio and total N content (kg ha^{-1}) are primary drivers of N supply to the subsequent crop (Finney et al., 2016; Tonitto et al., 2006; Vigil and Kissel, 1991; White et al., 2014). Legume cover crops can maintain a low tissue C:N ratio and accumulate a high biomass N content, leading to a high N supply from decomposing residues. On the other hand, grass cover crops tend to have a tissue C:N ratio that increases with plant maturity (Greenwood et al., 1990), so N supply becomes dependent on the timing of cover crop termination (Clark et al., 2007a, 1994; Vaughan and Evanylo, 1998), and is usually lower than that from legumes (Miguez and Bollero, 2005). In grass-legume cover crop bicultures, the grass component can dilute the N content and increase the C:N ratio of the mixture, reducing the N supply potential relative to a legume monoculture (Benincasa et al., 2010; Brainard et al., 2012; Ranells and Wagger, 1997; Tosti et al., 2012). In bicultures, the seeding rate of the grass species is an important management control that can influence the N content and C:N ratio of the mixture (Poffenbarger et al., 2015). A study comparing 4- and 8-species cover crop mixtures to the component species in monocultures found that inorganic N supply and yield benefits to a subsequent maize crop were negatively related to the cover crop biomass C:N ratio (Finney et al., 2016). The range of cover crop mixtures included in that study resulted in negative, neutral, and positive N supply depending on the species in the mixture and the site-year of the study, illustrating the high variability in the N supply service provided by cover crop mixtures and underscoring the need for management guidelines to optimize N supply from cover crop mixtures.

Cover crops that are able to scavenge and assimilate large amounts of soil NO_3^- during periods of high leaching potential increase N retention in agroecosystems. Legume cover crop species retain less N than non-legume species (Finney et al., 2016; Shipley et al., 1992; Tonitto et al., 2006) because they meet some of their N demand through atmospheric N fixation and are consequently less aggressive scavengers of soil NO_3^-. Finney et al. (2016) found that N retention by cover crop monocultures and mixtures was positively related to the cover crop C:N ratio, an indicator representing the relative contribution of legume and non-legume species to the cover crop biomass. In that study, all cover crop mixtures that contained winterhardy non-legume species provided a positive N retention service relative to the fallow treatment, whereas mixtures in which the only non-legumes were winter-killed species had variable levels of N retention across site-years. Winter-killed cover crops may not be as effective as winterhardy cover crops for N retention because decomposing residues can mineralize N in early spring when the leaching potential is still high (Dean and Weil, 2009) and because the shorter growing season for winter-killed species may reduce the total N assimilation potential relative to winterhardy species (Kaspar et al., 2012).

While cover crop mixtures could enhance the dual provisioning of N retention and N supply services relative to cover crop monocultures, cover crop management practices that minimize the tradeoffs between these services are currently not well understood. Furthermore, the multiple environmental controls, cover crop management practices, and cover crop functional traits that likely interact to affect the tradeoffs between N retention and N supply services have not been analyzed as a system across a range of conditions representative of commercial farming practices. In this study we measured the N retention and supply services provided by cover crops in distributed experiments across Pennsylvania, USA and developed multiple linear regression models to predict N retention and supply based on cover crop functional characteristics and environmental variables. We then synthesized the system of regression models into a graphical analysis tool and used the tool to identify management practices that could minimize the tradeoff between N retention and supply.

2. Materials and methods

2.1. Study sites, experimental design, and crop management

Farmer participatory experiments were located on three commercial organic farms in different regions of Pennsylvania (Berks, Lancaster, Montour counties) and a companion research station experiment was located at the Russell E. Larson Agricultural Research Center in Centre County, Pennsylvania. Site characteristics are described in Table 1. In the experiments conducted on commercial farms, the farmers selected two cover crop treatments: (1) a cover crop monoculture representative of the typical cover crop practice on the farm and (2) a 3-species cover crop mixture designed to meet management objectives specific to the farm (Table 2). A third treatment, a uniform 4-species cover crop mixture, was used on all commercial farms as well as the research station experiment. The research station experiment contained at total of 12 cover crop treatments including no cover crop, monocultures of 6 different species, and 5 multi-species mixtures (Murrell et al., 2016). However, in this analysis we only include treatments from the research station that were similar to treatments used in the on-farm experiments, which included two monoculture species, a 3-species mixture designed for N management, and the 4-species mixture used across all sites (Table 2).

Cover crop treatments were arranged in a randomized complete block design with four replications. Plot dimensions varied based on the size of the production field used in each location and year, with a minimum plot dimension of 7×20 m and a maximum plot dimension of 21×120 m. Experiments were repeated twice in different fields at each on-farm location with starting years in 2012 and 2013. At the research station, cover crop plantings in 2012, 2013, and 2014 were entry points in a full-entry crop rotation experimental design that began in April 2012 using a winter wheat (*Triticum aestivum* L.)-cover crop-maize (*Zea mays* L.) –cover crop-soybean (*Glycine max* (L.) Merr.) rotation. The research station