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Reduced nitrogen losses after conversion of row crop agriculture to alley cropping with mixed fruit and nut trees

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ABSTRACT

Agriculture across the temperate zone is dominated by a maize-soybean rotation (MSR) characterized by a "leaky" nitrogen (N) cycle. MSR N losses have considerable negative impacts on water quality via N leaching and climate change via soil emissions of nitrous oxide (N_2O), a potent greenhouse gas. Alley cropping (AC) focused on food- or fodder-producing tree crops has the potential to substantially reduce environmental N losses while maintaining agricultural productivity. To compare the N cycling of MSR and AC, this study (1) summarized literature values of N pools and fluxes in both systems, (2) directly measured N leaching and N_2O emissions in a side-by-side trial of MSR and an establishing AC over four years, and (3) used AC yield projections to estimate the trajectory of yield-scaled N losses as AC grows to productive maturity. Ample literature data on MSR permitted the construction of a robust working N budget, while a paucity of existing data on N cycling in AC revealed gaps and high uncertainty in our existing knowledge. In the field trial, AC quickly reduced both N leaching and N_2O emissions compared to MSR. Nitrate leaching at 50 cm depth in MSR ranged from 21.6 to 88.5 kg N ha^{-1} yr^{-1}, whereas leaching was reduced by 82–91% in AC. Cumulative annual net N_2O fluxes in MSR ranged from 0.4 to 2.0 kg N ha^{-1}, but AC reduced annual fluxes by 25–83%. Overall, conversion of MSR to AC reduced unintended N losses over four years by 83% from 240 to 41 kg N ha^{-1}. Even when accounting for the low yield in AC during the establishment years studied here, yield-scaled N leaching in AC and MSR were not significantly different. In contrast, yield-scaled N_2O fluxes were an average of 4.8 times higher in AC across years and were only estimated to reach a comparable range to MSR after reaching productive maturity. Our results demonstrate rapid tightening of the N cycle and a competitive trajectory of yield-scaled N losses as row crop agriculture is converted to AC.

1. Introduction

Row crop agriculture is a dominant land-use around the world, with maize and soybean alone covering over 346 million hectares worldwide (FAO, 2017). The maize-soybean rotation (MSR) typically relies on large nitrogen (N) inputs and intensive disturbance, which can increase environmental N losses. The two most concerning avenues of unintended N loss from agricultural systems are N leaching and soil nitrous oxide (N_2O) emissions (David et al., 2009; Hernandez-Ramirez et al., 2009). In North America, agricultural N leaching contributes around 80% of the 1.2 million tons of N entering the Gulf of Mexico and results in hypoxia (David et al., 2010; USEPA, 2007). Although the absolute amount of N lost via N_2O emissions is small, N_2O is a potent greenhouse gas and driver of climate change (IPCC, 2014). The leaky agricultural N cycle produces 55% of global N_2O emissions (USEPA, 2012). Ammonia (NH_3) volatilization can also contribute substantial N loss, with an average of 18% of applied N lost as NH_3 globally (Pan et al., 2016) and as much as 46% of applied N lost in temperate pasture systems (Vaio et al., 2008). Many agronomic techniques have been proposed to reduce N losses from row crop agriculture, such as adjusting N fertilization to crop needs, application of nitrification inhibitors, cover crops, and water management in irrigated crops (Abalos et al., 2016; Quemada et al., 2013). A meta-analysis of the many techniques intended to reduce N losses in maize found that they can reduce N leaching by 14–37% and N_2O emissions by 5–40% (Xia et al., 2017). However, much greater reductions are needed to meet hypoxia reduction goals (Scavia et al., 2004) and climate change mitigation goals (IPCC, 2014).

Alley cropping (AC), the integration of trees with crops, is a

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transformative departure from the incremental improvements to MSR that focus on minor agronomic improvements or field margins (Gold and Hanover, 1987; Wilson and Lovell, 2016). In particular, AC with food- or fodder-producing "tree crops" (e.g. nut or fruit trees), could maintain high agricultural yields while promoting substantial ecological benefits in a "land sharing" land-use approach (Anderson-Teixeira et al., 2012; Lovell et al., 2017; Wolz et al., 2018). By integrating trees and crops throughout a field, temperate AC can promote carbon sequestration, improved soil structure, increased biodiversity, and soil stabilization (Jose, 2009; Thevathasan and Gordon, 2004; Tsonkova et al., 2012). In addition, AC has potential to reduce N losses.

Like cover crops or buffer strips, tree roots can provide a "safety-net" by catching N that leaches beyond the crop rooting depth or growing season (Allen et al., 2004). For example, AC reduced nitrate (NO_3^-) leaching compared to monoculture crops by 46% at 0.3 m depth and 71% at 0.9 m depth (Allen et al., 2004). The greater leaching reduction with depth illustrates the cumulative effect of tree roots. Lower in the soil profile, Dougherty et al. (2009) found 46% lower NO_3^- levels in tile effluent under AC than monoculture maize, which directly translates into impacts on surface water quality. Even compared to perennial pasture, which has deeper roots and a longer growing season than annual crops, integrating trees reduced peak NO_3^- concentrations at 1.2 m depth by 56% (Bambo et al., 2009). The efficacy of leaching reductions in AC varies with alley crop species (Dai et al., 2006) and soil texture (Bergeron et al., 2011).

Agroforestry also has potential as a mitigation tool for climate change through reduced N_2O emissions (Schoeneberger et al., 2012). For example, studies of hedgerows and shelterbelts found up to 74% lower N_2O emissions compared to adjacent cropland (Amadi et al., 2016; Baah-Acheamfour et al., 2016). However, in a synthesis of N_2O emissions in agroforestry, Kim et al. (2016) reported an increase of annual N_2O emissions of 0.64 ± 0.26 kg N ha^{-1} in AC compared to adjacent agricultural fields. This value was based on only a single study (Guo et al., 2009) – the only study of N_2O emissions in AC with sufficient sampling to generate annual flux estimates – and clearly demonstrates the paucity of data on N_2O emissions in AC. Although not providing an annual total, Beaudette et al. (2010) found that AC reduced soil N_2O emissions by 72% on four dates without impacting alley crop yields.

Studies of N cycling in AC have focused on mature systems, leaving uncertain the trajectory of N losses during establishment. Other perennial crops can reduce N losses soon after conversion from MSR. For example, perennial grasses grown as bioenergy crops reduced NO_3^- leaching and N_2O emissions by over 90% in just four years (Smith et al., 2013). Young woody bioenergy crops can reduce NO_3^- leaching by more than 99% over the first 11 years (Syswerda et al., 2012) and N_2O emissions by 81% over the first nine years (Robertson et al., 2000). It is important to note, however, that perennial bioenergy crop are typically not fertilized due to the wide C:N ratios of the harvested biomass. Instead, fertilization can increase N losses unnecessarily (Balasus et al., 2012; Behnke et al., 2012). In contrast, AC with tree crops will likely require greater N replenishment due to the narrower C:N ratios of fruit/nut yields. These higher N inputs could negate the potential of AC to reduce N losses.

As a land sharing approach, a complete comparison of AC with MSR requires the use of yield-scaled N losses (Linquist et al., 2012), in which N losses are scaled by caloric food yields to determine N loss per unit yield. The yield-scaled concept has only recently been applied in perennial crops (Schellenberg et al., 2012) but is especially important when comparing AC and MSR due to the low yields of immature tree crops and the contrasting fertilization regimes typically used. Many years of high yield-scaled N losses during the establishment phase could outweigh lower values at maturity.

Understanding the N cycle of AC is critical for its evaluation as a viable agricultural practice in the temperate zone. The objective of this study was to quantify changes in the N cycle when transitioning from MSR to AC. Three approaches were used: (1) To provide context on the possible range of N pools and fluxes in temperate MSR and AC, we constructed working N budgets from literature values and agricultural statistics. (2) We conducted a side-by-side trial of AC and MSR to evaluate changes in the N cycle over the first 5 years after AC establishment. (3) Using projections of AC yield, we estimated the trajectory of yield-scaled N losses as AC grows to reproductive maturity. We hypothesized that transitioning from MSR to AC would (1) substantially reduce N losses, although (2) yield-scaled N losses would only become competitive with MSR once the tree crops reach reproductive maturity.

2. Materials and methods

2.1. Working N budgets

Working N budgets for MSR and temperate AC were constructed using a combination of agricultural statistics, climate statistics, and literature values. Literature values were primarily gathered from existing reviews of various components of the N cycle. All budget values were summarized as ranges, with values greater than 20 kg N ha^{-1} yr^{-1} rounded to the nearest 10 units. Complete details on the derivation of N budgets are provided in the Supplemental Materials.

2.2. Site description and experimental design

Our study site was located at the University of Illinois Pomology Research Farm (40°4′45.05″N, 88°12′57.45″W, ~220 m above sea level). The site previously grew soybeans (2009–2011), silage maize (2006–2008), and alfalfa (2002–2005), although was historically in a traditional MSR. Average annual temperature during the study ranged from 9.8–12.9° C, and annual precipitation ranged from 861 to 1331 mm (Illinois Climate Network, 2017). Monthly precipitation and temperature data are shown in Tables S1 and S2. Soils are a Flanagan silt loam (Fine, smectitic, mesic aquic agriudolls), typical of the deep, poorly drained mollisols of central Illinois. At the time of establishment, mean organic C content in the top 30 cm of soil ranged from 17.3–25.2 g kg^{-1}, and soil pH was 7.3. The study site has a ~2% slope and contains four-inch drain tile oriented E to W at 30 m spacing.

The two treatments studied were: MSR and an establishing AC. Plots were established in spring 2012 in a randomized complete block design with four 0.2-ha replicates and mowed grass buffers (Fig. 1). Neither treatment was irrigated during the study period. MSR was managed using typical practices of central Illinois. Soybean was planted in 80-cm rows on 17 May 2013 and 22 May 2015. Maize was planted in 75-cm rows in 23 Apr. 2014 and 6 May 2016. Glyphosate was applied in all years approximately one month after planting. Grain harvest was completed on 28 Oct. 2013, 18 Nov. 2014, 22 Oct. 2015, and 5 Oct. 2016. All MSR plots were conventionally tilled annually.

The AC design was based on Shepard (2013), containing six different food-producing tree and shrub species with grass-clover hay alleys (Fig. 1). Multiple tree and shrub species were included in the AC design because the site is part of a collection of experiments exploring the impact of tree crop diversity in AC (see Lovell et al., 2017; Wolz et al., 2018). Grass-clover alleys, rather than row-crop alleys, were included in this study because this is the approach most commonly used by farmers adopting AC in the region. All woody plants were planted between 12 May and 4 Jun. 2012, and the hay was seeded on 1 Oct. 2012. Except for raspberries, which had a 40% survival rate and were replanted on 19 May 2013, all species exhibited ~90% survival. Herbicide (29.4% S-metolachlor, 11% atrazine, 2.94% mesotrione) was applied prior to planting on 24 Apr. 2012. In 2013, a 1.4 m band of pre-emergent herbicide was applied in the tree rows (oryzalin) on 7 May and the alley crop (prodiamine) on 17 May. On 31 Jan. 2014, Dutch white clover was broadcast under the tree rows to serve as a living mulch. From 2014 on, the 0.5 m on either side of tree rows was mowed monthly. Weeds within rows were managed using a string trimmer. To