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Fluxes of nitrous oxide and nitrate from agricultural fields on the Delmarva Peninsula: N biogeochemistry and economics of field management

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ABSTRACT

The effects of two agricultural conservation practices on nitrous oxide (N_2O) fluxes to the atmosphere and nitrate (NO_3^-) fluxes to groundwater were compared to conventional practices. The conservation practices were application of 80% of recommended nitrogen (N) and planting of winter cover crops. N_2O fluxes were measured by static chambers, and NO_3^- fluxes were calculated using measured NO_3^- concentrations from tile lines and estimated groundwater yields. During the growing season, one of the five 80% N treatments showed significantly reduced N_2O fluxes compared to the 100% N control, whereas three of the five 80% N treatments showed significantly reduced NO_3^- concentrations compared to the 100% N application. The 80% N treatment resulted in reduced crop yields of 5–26% and average economic losses of US$366 ha^{-1} for corn and US$153 ha^{-1} for winter wheat. In three winter cover-crop treatments there were two significant reductions in fall N_2O fluxes compared to no-cover-crop controls, and tile drain NO_3^- concentrations were also significantly lower in autumn. The N_2O fluxes were a function of soil temperature, moisture, and fertilizer applications ($r^2 = 0.49$, $p < 0.001$). Integrating N_2O and NO_3^- fluxes to the annual time scale without conservation measures resulted in mean export of 15 ± 8 kg N_2O-N ha^{-1} y^{-1} and 36 ± 6 kg NO_3-N ha^{-1} y^{-1}. Adding an 80% N conservation treatment reduced N_2O fluxes by 79% and NO_3^- fluxes by 22%, whereas adding cover crops had smaller effects (11% for N_2O, 9% for NO_3^-). However, cover crops were more cost-effective, averaging US$53 (kg N)$^{-1}$ compared to the 80% fertilizer treatment (US$77 (kg N)$^{-1}$) due to large economic losses for corn. The state of Maryland (MD) subsidizes cover crops, making the practice even more cost-effective at US$15 (kg N)$^{-1}$, emphasizing the importance of farmer-friendly policies.

1. Introduction

Climate change, water quality, and population growth are three of the most important environmental issues today (Davidson et al., 2015). The United Nations Sustainable Development Goals are intended to end hunger, combat climate change, and sustainably manage our terrestrial, coastal, and oceanic areas. Each of these goals is significantly impacted by our global food production system (United Nations, 2015). Maintaining and improving the viability of agriculture is necessary to meet the food demands of the growing global population (Tilman et al., 2002); however, food production significantly contributes to emissions of the greenhouse gas nitrous oxide (N_2O) leading to global climate change (IPCC, 2016) and to fluxes of nitrate (NO_3^-) which accelerates water quality decline (e.g., Mitsch et al., 2001; Fisher et al., 2006, 2010; Saaltink et al., 2014). Improved agricultural management is required to reduce the impacts of agriculture on climate change and water quality, while feeding the growing world population.

Agricultural soils are the primary anthropogenic source of N_2O (Davidson and Kanter, 2014). N_2O is a powerful greenhouse gas (GHG) with an average atmospheric longevity of 114 years and a 100-year global warming potential of 298 (IPCC, 2016). Additionally, N_2O is the most prominent sink for stratospheric ozone in the 21st century (Ravishankara et al., 2009). Although N_2O accounts for only 6% of the total GHG emissions from human activities in the US (USEPA, 2016a),

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agricultural soil contributes ~79% of US N_2O emissions (USEPA, 2016b). Therefore, mitigating agricultural N_2O is a critical component of addressing climate change (CAST, 2004; Venterea et al., 2012).

Agriculture is also the leading contributor of nonpoint source (NPS) nitrogen (N) pollution to ground and surface waters in the US (USEPA, 2009; Dubrovsky et al., 2010 Dubrovsky et al., 2010). Dissolved nitrate (NO_3^-), the most mobile form of N, readily leaches from agricultural soils into groundwater of the surface, unconfined aquifer. High groundwater NO_3^- concentrations have been measured under agricultural areas across the US, and these concentrations sometimes exceed the 10 mg N L^{-1} drinking water limit set by the US EPA (e.g., Böhlke and Denver, 1995; Mueller and Helsel 1996; Fisher et al., 2010; Exner et al., 2014). Agricultural groundwater flows down hydraulic gradients and eventually emerges in streams, rivers, and estuaries as NPS N pollution, although groundwater NO_3^- can be attenuated by denitrification in hydric soils (Lee et al., 2001; Fox et al., 2014). Stream NO_3^- concentrations draining largely agricultural watersheds typically fall in the range of 150–1100 μM NO_3^- (2–15 mg NO_3-N L^{-1}; e.g., Grimvall et al., 2000; Dubrovsky et al., 2010), and positive relationships between concentrations of stream NO_3^- and percentages of agriculture within watersheds have been widely reported (Jordan et al., 2003; Mitchell et al., 2009; Fisher et al., 2010; Thorburn et al., 2013). Streams draining agriculturally dominated watersheds degrade downstream water quality, which is widely observed (e.g, Chesapeake Bay: Kemp et al., 2005, Gulf of Mexico: Rabalais et al., 2002, Black Sea: Zaitsev and Alexandrov, 1997, Baltic Sea: Bonsdorff et al., 1997, Great Barrier Reef: Brodie et al., 2011).

Emission of N_2O to the atmosphere and leaching of NO_3^- to groundwater are linked processes. N fertilizers are typically applied as reduced or organic forms of N (e.g., anhydrous ammonia, urea, manure), and in the presence of oxygen, nitrifying soil bacteria oxidize NH_4^+ to NO_3^- with N_2O produced as a byproduct (Papen et al., 1989; Wrage et al., 2001; Butterbach-Bahl et al., 2013). The NO_3^- resulting from these processes is highly soluble and easily leached to groundwater during infiltration. NO_3^- is transported by groundwater towards streams and can be denitrified to N_2 and N_2O. Both nitrification and denitrification can increase N_2O concentrations in groundwater and the vadose zone, resulting in N_2O fluxes to the atmosphere from soil or stream surfaces. These fluxes have been shown to account for a large fraction of all N fluxes in agricultural watersheds (Vilain et al., 2012; Gardner et al., 2016).

N_2O production in soils occurs under specific conditions. Large fluxes of N_2O have been observed after fertilizer addition (Khalil et al., 2002; Dobbie and Smith 2001, 2003; Luo et al., 2013), after soil rewetting (Ruser et al., 2006), and following rain events (Dobbie and Smith 2001, 2003). N_2O fluxes from soils are typically produced by denitrification at > 60% water-filled pore space (%WFPS), and by nitrification at lower (30–50%) WFPS (Davidson et al., 2000; Khalil and Baggs 2005; Bateman and Baggs 2005). Studies suggest strong relationships between N_2O flux and soil N content, net nitrification, soil diffusivity, organic matter incorporation, and N applications (Eickenscheidt and Brumme 2013; Luo et al., 2013; Rees et al., 2013; Kravchenko et al., 2017). N_2O production and flux also typically increase with temperature (Smith and Dobbie 2001; Luo et al., 2013) and soil moisture (Xiong et al., 2006; Luo et al., 2013). A recent review by Jurado et al. (2017) summarizes much of this literature.

Fertilizer management has been shown to control N_2O fluxes. Amount of fertilizer significantly influences N_2O flux rates (e.g., Stehfest and Bouwman, 2006), and N_2O emissions respond non-linearly to increasing fertilizer rates as N inputs satisfy crop N demand in research plots (McSwiney and Robertson, 2005), commercial farm fields (Hoben et al., 2011), and in grain crops globally (Shcherbak et al., 2014). Fertilizer type has a strong (e.g., Eichner 1990; Bouwman et al., 2002; Venterea et al., 2010) or no impact on N_2O fluxes (e.g., Luo et al., 2013).

On-field management has also been reported to impact N_2O fluxes. Drury et al. (2012) found a 44% reduction in N_2O flux from zone tillage, and a 17% reduction from no-tillage in comparison to conventional tillage. A meta-analysis of 26 peer-reviewed publications by Basche et al. (2014) showed that winter cover crops decreased N_2O fluxes during some parts of the year and increased them during others, especially if cover crops were killed with herbicide or if cover crop residues were tilled. However, at the annual time scale these effects nearly balanced, resulting in no significant difference between cover crop and no cover crop treatments. Crop type can also impact N_2O flux, and Bouwman et al. (2002) reported generally lower fluxes of N_2O from leguminous crops (e.g., soybeans) in comparison to other crops (e.g., corn). However, management effects can be overshadowed by weather events that impact soil temperature and soil moisture, and Rees et al. (2013) suggested the importance of managing agricultural systems with a regional perspective, considering local climatic and soil conditions.

Management practices have also been investigated to evaluate their impacts on NO_3^- losses to groundwater and surface water (Bohlke and Denver 1995; Webster et al., 2012). NO_3^- leaching is related to nitrogen use efficiency (NUE), which is usually expressed as% of fertilizer or manure N removed as grain N. Worldwide, NUE of grain production is 30–50% (Cassman et al., 2002), and the fraction of the fertilizer N left in soil or plant tissues after harvest is the source of NO_3^- leaching. Increased N fertilizer applications have been found to linearly increase NO_3^- leaching to groundwater (Gehl et al., 2006; Zhou and Butterbach-Bahl 2014). Therefore, reducing N application rates (e.g., Webster et al., 2012) or increasing NUE could decrease NO_3^- leaching to groundwater. Although crop yields could decrease with lower N-fertilizer applications (Zhou and Butterbach-Bahl, 2014), yields could also be maintained by increased NUE.

Agricultural management can range across a spectrum of approaches. Traditionally, farm management has been based on maximizing yields and farm profit with little consideration of environmental effects external to the farm. In contrast, strict environmental management of farm fields has focused on reducing nutrient and sediment losses with limited consideration of farm profit. A more balanced approach has focused on reporting N losses to the environment normalized to crop yield (Van Groenigen et al., 2010; Venterea et al., 2011; Drury et al., 2012; Zhou and Butterbach-Bahl 2014; Roebeling et al., 2014). A parallel approach is N cost-effectiveness for a practice, defined as the cost of a Best Management Practice (BMP) per unit agricultural N captured, reported as US$ (kg N)$^{-1}$. The N cost-effectiveness is a useful metric for the best allocation of limited conservation resources (Wieland et al., 2009; Christianson et al., 2013).

Moving forward, sustainable management of agricultural fields must take into account farm economics (Bøckman and Olfs, 1998) and environmental impacts (Foley, 2017). Below we present empirical data on the effects of two conservation practices on N_2O and NO_3^- fluxes, soil properties, agronomic yields, and farm and regional economics for three corn/wheat/soybean rotation fields of a farm in Caroline County, Maryland (USA). We collected data on direct measurements of N_2O fluxes using static chambers and manually collected samples from tile lines for NO_3^- analysis. All measurements were made in fields with treatments of 100 or 80% of regionally recommended N rates on corn based on soil N tests in June after planting, both with and without winter cover crops. Our hypothesis is that the 80% N treatment and presence of winter cover crops reduce fluxes of N_2O and tile drain NO_3^- losses in comparison to traditional management. We tested the hypothesis, evaluated the cost effectiveness of the two management practices, and developed an efficiency analysis comparing private costs to the farmer and the social benefits of implementing these management practices. This study appears to be one of very few U.S. studies that examines the impact of alternative field management on both NO_3^- and N_2O losses and assesses the economic implications for the farm and society.