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Nitrous oxide (N_2O) flux responds exponentially to nitrogen fertilizer in irrigated wheat in the Yaqui Valley, Mexico

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ABSTRACT

The Yaqui Valley, one of Mexico's major breadbaskets, includes ~230,000 ha of cultivated, irrigated cropland, with two thirds of the area planted annually to spring wheat (*Triticum turgidum)*. Nitrogen (N) fertilizer applications to wheat have doubled since the 1980s, and currently average around 300 kg N ha^{-1}. Emissions of nitrous oxide (N_2O), a potent greenhouse gas, increase following soil management activities, especially irrigation when N fertilizer is applied, and particularly when N fertilizer inputs exceed crop N requirements. Here we investigate trade–offs among N fertilizer inputs, spring wheat yields, and N_2O emissions to inform management strategies that can mitigate N_2O emissions without compromising yields, and link this to how farmers can generate carbon credits from N management to receive payment for more precise N use. We used static chambers to measure N_2O fluxes from spring wheat at five N fertilizer rates (0, 80, 160, 240, and 280 kg N ha^{-1}) during two growing seasons at CIMMYT in Ciudad Obregon, Sonora, Mexico. Average daily fluxes were between 1.9 ± 0.5 and 13.4 ± 2.8 g N_2O-N ha^{-1}, with lower emissions at N rates below those that maximized yield, and substantially higher emissions at N rates beyond maximum yield; this exponential response is consistent with crops in temperate regions. Results suggest that current average N fertilizer rates (300 kg N ha^{-1}) are at least double economically optimum rates, resulting in low crop N use efficiency: 36–39% at higher N rates as compared to 50–57% for economically optimum rates. N fertilizer rate reductions to the economic optimum rates here (123 and 145 kg N ha^{-1} in 2013 and 2014, respectively) could have avoided N_2O emissions equivalent to 0.5 to 0.8 Mg CO_2e ha^{-1} yr^{-1} or, regionally, 84–138 Gg CO_2e yr^{-1} without harming yields. Insofar as fertilizer use in Yaqui Valley is likely similar to high-productivity irrigated cereal systems elsewhere, our results provide evidence for a global triple-win scenario: large reductions in agricultural GHG emissions, increased farmer income, and continued high productivity.

1. Introduction

Nitrous oxide (N_2O), a potent greenhouse gas (GHG) that contributes to atmospheric warming and stratospheric ozone depletion (IPCC, 2007) is produced in soils mainly by microbial denitrification and nitrification (Panek et al., 2000; Robertson and Groffman, 2015). Agriculture contributes ~60% of global anthropogenic N_2O emissions (Tian et al., 2016; Robertson, 2014), mostly due to the application of nitrogen (N) fertilizer to croplands (Syakila and Kroeze, 2011).

In Mexican agriculture N_2O from cropped soils is the second largest source of GHG emissions (World Bank, 2015) and wheat (*Triticum* spp.) is one of the most important fertilized crops, grown on over half a million hectares in Mexico in 2016, nearly a quarter as irrigated spring wheat grown in the semi-arid Yaqui Valley (SIAP, 2017). Yaqui Valley wheat yields are high, typically 5.2–7.0 Mg ha^{-1} y^{-1} (SAGARPA, 2016), with N fertilizer applications averaging ~300 kg N ha^{-1} (Ortiz-Monasterio, 2017), a near doubling since the 1980s that coincides with adoption of the variety CIRNO C2008 with its high yields and low tolerance for N stress. High rates of fertilization can result in significant N losses to the environment via leaching, run-off, and N_2O emissions (Matson et al., 1998; Riley et al., 2001; Beman et al., 2005, Ortiz-Monasterio and Raun, 2007) stemming from recoveries of only ~30% of fertilizer N in harvested grain (Raun and Johnson, 1999).

That N fertilizer rate is the best available single metric for predicting

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agricultural N_2O fluxes (Stehfest and Bouwman, 2006) suggests a potential for reducing fluxes by improving N fertilizer use efficiency (Eagle et al., 2012), and carbon credit organizations have expressed interest in using the carbon marketplace to pay farmers for more precise N management (Millar et al., 2010). The most accessible carbon credit programs for N management (Millar et al., 2012; 2013) use methodologies that incorporate emission-factor (EF)-based algorithms to estimate N_2O emissions reductions as a percentage of avoided N use. In the absence of regional experimental evidence, protocols default to the standard EF of 1% (de Klein et al., 2006) used in most national GHG inventories (Lokupitiya and Paustian, 2006). A 1% EF means that 1 kg of N_2O-N is emitted for every 100 kg of N fertilizer applied. Avoided N_2O emissions are then converted to units of avoided carbon dioxide equivalents (CO_2e) based on N_2O's global warming potential, about 300 times greater than CO_2's (IPCC, 2007). Avoided CO_2e emissions can then be traded as carbon credits on environmental markets to generate income.

Recent evidence suggests that a 1% EF may underestimate emissions at fertilizer rates that exceed crop need (Hoben et al., 2011; Shcherbak et al., 2014), especially in high-productivity agriculture such as practiced in the Yaqui Valley. If so, then under a 1% EF scenario farmers would receive fewer credits than merited, reducing incentives for better N management and the environmental benefits that would accrue. However, there are no studies of N_2O response to added fertilizer N in semi-arid irrigated agriculture.

Our objectives here are 1) to investigate the trade–offs among N fertilizer input, N_2O emissions, and spring wheat yield in order to inform management strategies that can reduce N_2O emissions without compromising yields, and 2) to develop emission factor algorithms suitable for inclusion in N_2O mitigation protocols to help farmers use carbon markets to generate additional income from improved N management. More globally, we test the hypothesis that N_2O emissions response to fertilizer N is exponential in semi-arid, sub-tropical irrigated agriculture.

2. Materials and methods

2.1. Region

The Yaqui Valley is located in NW Mexico, on the west coast of Sonora, bounded on the west by the Gulf of California and on the east by the foothills of the Sierra Madre. Agroclimatic conditions are representative of regions in the developing world that produce 40% of the world's wheat (Pingali and Rajaram, 1999). The area comprises ~230,000 ha of irrigated cropland, predominantly spring wheat, with maize, safflower, chickpeas, vegetable crops, and cotton, among others, also grown. Wheat growing season (November to April) temperatures average 9.8 and 27.1 °C for night- and daytime, respectively. Soils in the valley are predominantly vertisols and aridisols, with elevations varying from 0 to 60 m asl (Ortiz-Monasterio and Raun, 2007).

2.2. Site and management

Experimental plots (3.2 × 5.0 m; each containing four planting beds) were established in Yaqui Valley at Campo Experimental Norman E. Borlaug (CENEB; Block 810), near Ciudad Obregon, Sonora, Mexico (27°N; 109°W, 40 m asl) using a randomized complete block design (eight treatments; six replications). Plots were planted to spring wheat (*T. turgidum* var. durum; cultivar CIRNO C-2008) during the 2012–2013 and 2013–2014 growing seasons. The soil is a coarse, sandy clay mixed montmorillonite classified as a Typic Caliciorthid. Treatments were N fertilizer rates of 0, 40, 80, 120, 160, 200, 240, and 280 kg N ha^{-1} yr^{-1}. Spring wheat was planted as two rows on top of each bed (26 cm apart) at a density of 120 kg seed ha^{-1} using a Wintersteiger plot planter on 28 November 2012 and 13 December 2013 (within the recommended planting date range). Triple super phosphate (20 kg P ha^{-1}) was applied pre-planting and disk incorporated. N fertilizer (granular urea) was banded as a single dose by hand on the soil surface in each furrow after planting and immediately before furrow irrigation (29–30 November 2012, and 18–19 December 2013). Irrigation water was applied to the end of each furrow through the use of gated pipes, and was allowed to flow down the furrow and run out at the other end, until the top of the bed was fully wetted through capillarity. Unfertilized maize (grain and residue removed) was grown each year preceding the spring wheat as a catch crop for residual N. Herbicide (Starane Ultra; 0.4 L ha^{-1} and Broclean; 2 L ha^{-1}) was applied on 17 January 2014. No herbicide was applied in 2013; plots were field cultivated on 8 Jan 2013, and hoed throughout the crop cycle. Insecticide (Muralla; 0.5 L ha^{-1}, and Allectus; 0.2 L ha^{-1}) was applied on 24 January and 18 February 2014, respectively. Fungicide (Folicur; 0.5 L) was applied on 21 February 2014. Grain was harvested on 22 April 2013 and 5 May 2014 from 4.8 m^2 in each plot using a Wintersteiger plot combine. Yields were estimated from grain weights at 12% moisture. Grain and straw N content were determined by Kjeldahl analysis. Meteorological data were collected using a Vantage Pro 2 Plus weather station system (Davis Instruments, Vernon Hills, IL).

2.3. Soil sampling

Soil samples (0–15 cm) were collected in bed and furrow positions on 45 and 49 occasions, respectively, during the 2012–2013 and 2013–2014 spring wheat growing seasons from five treatments (0, 80, 160, 240 and 280 kg N ha^{-1}) in four replications (Blocks 1–4). Samples were immediately transferred to the laboratory at CENEB, weighed, dried for 48 h at 75 °C and weighed again to determine gravimetric soil moisture and soil water-filled pore space. Duplicate sub-samples (9 g each) of fresh soil were extracted with 1 M KCl (90 mL), shaken (1 min), stored (24 h at 21 °C), re-shaken (1 min), rested (60 min), then filtered (Whatman® 1 µm GF/B glass microfiber). An aliquot (8 mL) was transferred to a Corning® 15 mL clear polypropylene (PP) centrifuge tube, and frozen for transfer to Michigan State University's W.K. Kellogg Biological Station (KBS) for analysis of ammonium and nitrate in either a continuous flow analyzer (Flow Solution IV; OI Analytical, College Station, TX, U.S.A.) or a flow injector analyzer (Lachat QuikChem 8500 Series 2; Hach, Loveland, CO, U.S.A.). Instruments were cross-calibrated and seven calibration samples were analyzed twice per analytical run on each instrument along with multiple check standards.

2.4. Greenhouse gas sampling and analysis

Static chambers (Matson et al., 1996) were positioned at 5 cm depths in the furrow and bed areas of each plot from five treatments (0, 80, 160, 240 and 280 kg N ha^{-1}) in four replications (Blocks 1–4). Gas fluxes were determined immediately prior to N fertilization (concurrent with furrow irrigation), on days 1, 2, and 3 after fertilization, on alternate days during the next two weeks, then twice weekly unless following a supplemental irrigation event (then on days 1, 2, 3, then as above) until harvest, for a total of 45 sampling events between 29 November 2012 and 23 April 2013, and a total of 44 sampling events between 13 December 2013 and 21 April 2014. In 2014, sampling continued once per month after harvest until September. Chamber headspace gas samples (10 mL) were collected via syringe four times at 10 min intervals from each chamber, transferred to storage vials (5.9 mL; Labco Ltd., Lampeter, UK) to over-pressure, and transported to KBS for analysis. Samples were analyzed for N_2O using gas chromatography with a 63Ni electron capture detector at 350 °C (Agilent Technologies 7890A, Santa Clara, CA, U.S.A.) coupled to a Gerstel MPS2XL auto-sampler (Mülheim An Der Ruhr, Germany). Seven calibration samples were analyzed four times, along with multiple blanks and check standards throughout each analytical run.

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