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Research paper

Ion exchange resin samplers to estimate nitrate leaching from a furrow irrigated wheat-maize cropping system under different tillage-straw systems

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ABSTRACT

Nitrate (NO_3-N) leaching from agricultural soils can lead to substantial losses of fertilizer nitrogen (N) and cause considerable contamination of aquatic ecosystems and groundwater. This study aimed at estimating NO_3-N leaching losses for three tillage-straw management systems in the intensely cropped Yaqui Valley, Northern Mexico using ion exchange resin samplers. To this end data were collected in 2013/2014 from a tillage experiment established in 2005 as a randomized complete block design with two replications and three subplots on a Hyposodic Vertisol. Tillage-straw treatments were conventionally tilled beds with incorporated crop residue (CTB-straw incorporated), permanent beds with crop residue retained at the surface (PB-straw retained) and permanent beds with residue burning (PB-straw burned). Ion exchange resin samplers were installed at 90 cm depth in a consecutive crop rotation of wheat (*Triticum durum* L.) and maize (*Zea mays* L.) for 6 and 5 months, respectively (from first pre-plant fertilization to harvest). Leaching losses were higher with maize than with wheat cultivation (68.2 and 53.5 kg ha^{-1} $season^{-1}$ NO_3-N; P = 0.25). Tillage-straw treatment did not significantly affect NO_3-N leaching in wheat, but it did in maize. NO_3-N leaching for wheat was 51.1 kg ha^{-1} $season^{-1}$ NO_3-N in CTB-straw incorporated, 60.8 kg ha^{-1} $season^{-1}$ NO_3-N in PB-straw retained and only 46 kg ha^{-1} $season^{-1}$ NO_3-N in PB-straw burned. For maize, overall leaching losses were highest for PB-straw retained (81.9 kg ha^{-1} $season^{-1}$ NO_3-N), followed by 75.6 kg ha^{-1} $season^{-1}$ NO_3-N for CTB-straw incorporated and 47.7 kg ha^{-1} $season^{-1}$ NO_3-N for PB-straw burned. Soil NO_3-N concentrations were significantly affected by sampling date and depth. PB-straw burned had highest residual soil NO_3-N after crop harvest. Ion exchange resins-based NO_3-fluxes displayed high spatial variability, therefore a large number of repetitions was necessary. As 19% of N applied to wheat and 34% of N applied to maize was lost through leaching, farming practices that could lower the risk of nitrate contamination during cropping should be promoted. Additional multi-annual studies are necessary to assess the effects of reduced irrigation, climatic variation and different fertilizer application on nutrient leaching in different tillage-straw systems of northwestern Mexico.

1. Introduction

Nitrogen fertilizer prices have risen more than 2.5-fold over the past decade due to cost increases of petrol products and transportation and an overall increasing global demand (Hirel et al., 2007; Huang, 2009; Agricultural Prices, 2013). Over the past 50 years, N fertilizer application has increased 20-fold and was 110 Mio t in 2013 (IFA, 2015). Its application is projected to increase to 180 Mio t by 2030 (FAO, 2011). NO_3-N can move easily with the drainage water beyond the root zone into surface and ground waters and due to sub-optimal soil, irrigation and fertilizer management, globally large amounts of N are lost through NO_3-N leaching (Cassman et al., 2002). An efficient and non-polluting approach to mineral fertilizer use is essential to prevent excessive N losses, particularly for irrigated, high-input agro-environments, such as our study area, from where eutrophication of water bodies and the destruction of water ecosystems have been reported (Matson et al., 1998; Mitsch et al., 2001; Beman et al., 2005). As high nitrate and nitrite in drinking water resulting from the transport of leachates in lakes,

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rivers and ground water may pose a risk to human and animal health, a concentration limit of 10 mg NO_3-N L^{-1} has been proposed (Townsend et al., 2003; Cecena and Vega, 2011).

In the 2013/14 wheat season in the Yaqui Valley, wheat was seeded on almost 200,000 ha and grain wheat yields averaged 6.2 t ha^{-1} (SAGARPA and SIAP, 2014). This included fertilizer application rates averaging 297 kg N ha^{-1} (Lares-Orozco et al., 2016) which in addition to enhanced leaching risks also represented farmers' highest component of direct production costs (Matson et al., 1998). Generally, 75% of mineral fertilizer is applied broadcast approximately 20 days before planting as urea or through injection of anhydrous ammonium. The remainder is applied near the first node stage of plant development (Ortiz-Monasterio and Raun, 2007). Although locally only a small percentage of total N inputs is reportedly transported via surface water to the coast of Sonora (< 4%; Ahrens et al., 2008), phytoplankton net production and macroalgae growth are altered and this leads to bottom water hypoxia which negatively affects the fishery industry (Piñón-Gimate et al., 2009).

In the Yaqui Valley it is common practice to grow winter wheat and summer maize on raised beds with furrow irrigation, incorporating residues through tillage after harvest. Summer maize is planted on around 6000 ha in the Yaqui Valley and yields 5–5.5 t ha^{-1}. In recent times, permanent beds, a conservation agriculture (CA) management practice under irrigated conditions, have been promoted to increase sustainability by reducing tillage to a minimum, only reshaping beds as needed, and retaining and distributing crop residues on the surface (Hobbs et al., 2008). Soils with minimum soil movement or permanent raised beds combined with residue retention were found reported to have larger and more water-stable aggregates than soils with residue removal or conventionally tilled soils (Limon-Ortega et al., 2006; Lichter et al., 2008). Improved aggregate stability prevents soil surface sealing. Additionally, CA systems were reported to have an increased number of earthworm biopores (Baumhardt and Lascano, 1996). As a result, water infiltration rates are generally higher on soils with minimum soil movement and residue retention than conventionally tilled soils with or without residue removal (Verhulst et al., 2011a,b). Higher infiltration rates increase the risk of increasing N leaching losses in CA systems (Boddy and Baker, 1990; Singh and Malhi, 2006). In contrast, various studies have found higher NO_3-N leaching under conventional tillage due to increased N mineralization (Angle et al., 1993; Randall and Iragavarapu, 1995; Jackson et al., 2003). Slower nitrification in zero-tillage during fallow periods could reduce the potential for NO_3-N leaching (Power and Peterson, 1998).

Most approaches to measure leaching losses in conventional agriculture are based on point measurements such as obtained by suction lysimeters (Wegehenkel et al., 2008; Goss and Ehlers, 2009) or suction plates (Siemens and Kaupenjohann, 2004; Kasteel et al., 2007). These methods allow a dynamic and time-specific soil-water-solution sampling, but suction lysimeters and plates have a limited suction range (~pf 3), water conductivity is too low for the capture of preferential flow and above-ground equipment hinders field operations, making it impossible to use normal farmer practice. The use of ion exchange resin samplers allows to determine cumulative leaching losses at the plot-scale if proper care is taken to maintain the original soil structure above the cartridges and there is no stagnant water loading the resins from below (Bischoff, 2009; Predotova et al., 2011; Siegfried et al., 2012). Several authors have confirmed the reliability of ion exchange resin samplers in cumulative nutrient-leaching studies (Lehmann et al., 2001; Lang and Kaupenjohann, 2004; Bischoff, 2007) where resins stay in the soil for the entire vegetative period and thus provide an accumulated value of nutrients passing through the soil profile (Skogley and Dobermann, 1996; Bischoff, 2007). Typically after harvest, resin samplers are removed from the soil and the adsorbed ions are extracted and analyzed in the laboratory (Schnabel, 1983; Skogley et al., 1996).

Previous studies in the Yaqui Valley have measured gaseous N emissions from soils (Matson et al., 1998; Panek et al., 2000) and streams (Harrison and Matson, 2003; Harrison et al., 2005), but studies on leaching losses are limited and based on lysimeter and suction cup measurements or modeling approaches (Riley et al., 2001). On the other hand resin samplers have never been used under these conditions. We hypothesized that high leaching losses would occur in all tillage treatments and both crops due to over-application of mineral N fertilizer and irrigation water that foment leaching in this long-term experiment. A second hypothesis was that resin samplers would capture a high variation of leaching phenomena due to deep cracks which are formed over the cycle when the soil is drying. This variation was expected to be even higher in PB-straw retained due to crop residues on the soil surface which lead to slower irrigation water movement and accumulation of straw in the furrows, hence influencing fertilizer accumulation and movement. The objective of this research was (1) the evaluation of resin samplers to estimate total leaching losses of nitrate ions under irrigated conditions in a Vertisol and (2) the quantification of N losses by nitrate leaching in different tillage management systems and for two different crops in a long-term experiment in the intensively cropped Yaqui Valley of northwest Mexico.

2. Materials and methods

2.1. Study site

The long-term cropping systems trial used is located at CENEB (Campo Experimental Norman E. Borlaug), near Ciudad Obregón, Sonora, Mexico (27.33°N, 109.09°W, 38 m a.s.l.). The site has an arid climate, with a 10 year (2004–2014) average annual rainfall of 346 mm and an annual reference evapotranspiration of 1747 mm. Between 1993 and 2014, total annual precipitation ranged from 160 to 570 mm. Rainfall is summer dominant and only 20% occurs during the wheat-growing season (November-May) (Verhulst et al., 2011b). During the 2013/14 growing cycle mean temperature was 19.7 °C for wheat and 29.7 °C for maize. Monthly average temperatures ranged from 8.5 °C minimum temperature in January 2014 to 38.9 °C maximum temperature in June 2014. Total rainfall was 55 mm for wheat and 363 mm for maize (Fig. 1).

The soil at the experimental site was classified as a Hyposodic Vertisol (Calcaric, Chromic) according to the World Reference Base soil classification system (IUSS Working Group, 2007) or a fine, smectitic Chromic Haplotorrert according to the USDA Soil Taxonomy system (Soil Survey Staff, 2010). Throughout the upper 2 m depth soil organic matter is < 1.2% with pH > 8. At 0–70 cm depth, the particle size fraction contains 33% sand, 17% silt, and 50% clay. At 70–120 cm depth, sand decreases to 24%, 16% silt, and clay increases to 60% (Verhulst et al., 2009). Detailed soil information can be found in Table 1.

2.2. Long term experiment

The long-term trial was established in 2005 and consists of 17 treatments, which differ in tillage-straw system and rotation. In this study, three common tillage treatments with a wheat-maize rotation were selected, (1) CTB-straw incorporated: conventionally tilled raised-beds (CTB; tilled after each crop with a disk harrow to 20 cm after which new beds were formed), wheat and maize residues were incorporated by tillage; (2) PB-straw burned: permanent raised-beds (PB; zero-tillage with repeated reuse of existing beds, which were reformed in the furrows without disturbance of the tops of the beds), residues of both wheat and maize are burned; (3) PB-straw retained: PB, maize and wheat residues are kept on the soil surface. Averaged since 2007, 8.3 t ha^{-1} maize residue and 5.8 t ha^{-1} wheat residue was incorporated in the CTB-straw retained per year, while 10.0 t ha^{-1} maize residue and 6.5 t ha^{-1} wheat residue per year was retained on the PB-straw retained. In the PB-straw burned, on average 8.8 t ha^{-1} maize residue and 5.8 t ha^{-1} wheat residue was burned per year. The