Agricultural Water Management 212 (2019) 399–406

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Effect of cover crops on leaching of dissolved organic nitrogen and carbon in a maize-cover crop rotation in Mediterranean Central Chile

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ARTICLE INFO

Keywords:
Agriculture
Water quality
Diffuse pollution
Soil percolation
Nitrogen and carbon loads

ABSTRACT

Protection and management of water quality across agricultural landscapes requires a sound understanding of runoff and/or leaching of nutrients and other agrichemicals from agricultural production systems to receiving waters. We, in a large leaching columns experiment, studied the losses of dissolved organic N (DON), dissolved organic carbon (DOC), dissolved inorganic N (DIN) and total dissolved N (TDN) from maize cultivation on a coarse-textured soil in in Mediterranean Central Chile. The combined effects of cover crops and inorganic N fertilisation rates were evaluated on nitrogen and carbon leaching loads (DIN, DON and DOC) and ratios of soluble components (DON:DIN, DON:TDN and DOC:DON). A total of 52 soil columns for 13 treatments (4 replicates) were established to evaluate leaching of dissolved N and C forms from: 1) continuous bare soil (fallow) compared with a continuous cover crop (*Lolium multiflorum* or *Trifolium repens*), with 0 or 150 kg N ha^{-1} applied; and 2) maize-fallow and maize-cover crop rotations with two different N doses (250 or 400 kg N ha^{-1}) for the maize and cover crops (*L. multiflorum* and/or *T. repens*). We found that inclusion of a grass cover crop (*L. multiflorum*) and optimal N fertilisation (250 kg N ha-1) treatment resulted into lower DIN losses from the study columns. However, in trial 1, the DON load from the treatments with continuous grass cover crop *L. multiflorum* was on average twice the DIN load. In trial 2, the crop rotation of maize cultivation with 400 kg N ha^{-1} applied and inclusion of a legume cover crop *T. repens* resulted into the highest DIN loads, while a crop rotation of maize with 250 kg N ha^{-1} applied and inclusion of a grass cover crop *L. multiflorum* had the lowest DIN loads. However, the latter rotation gave significantly higher DON loads than the maize-fallow treatments. In trials 1 and 2, inclusion of *L. multiflorum* enhanced soil organic pools and microbial activity, and thus increased the amount of DON and DOC susceptible to leaching. Overall, the rotation with maize with 250 kg N ha^{-1} applied and *L. multiflorum* as cover crop generated the lowest amount of TDN leaching from the soil columns. We recommend this to be further studied in field conditions as a best management practice for reducing the risk of diffuse pollution of surface water bodies and groundwater from maize cultivation in Mediterranean Central Chile.

1. Introduction

Protection and management of water quality across agricultural landscapes requires a sound understanding of runoff and/or leaching of nutrients and other agrichemicals from agricultural production systems to receiving waters. Dissolved inorganic nitrogen (DIN) forms, such as nitrate (NO_3-N) and ammonium (NH_4-N), have been identified as the main forms of nitrogen (N) leaching in agricultural systems (Galloway et al., 2008; Vitousek et al., 2009; Salazar et al., 2013). However, recent studies include dissolved organic N (DON) leaching as another important N loss pathway from agroecosystems (Abaas et al., 2012; McGovern et al., 2014; Scott and Rothstein, 2014). According to van Kessel et al. (2009), it has been known for more than 125 years that DON leaching losses occur from agricultural fields, but most N loss studies on agricultural systems have not measured DON as a potential pathway. Jones et al. (2004) concluded that DON is an important soluble N pool within total dissolved nitrogen (TDN) in soil and, although its full ecological significance remains unknown, they recommend measuring DON on a routine basis alongside measurements of DIN losses from agricultural soils. Dissolved organic N losses could explain a

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https://doi.org/10.1016/j.agwat.2018.07.031
Received 7 April 2018; Received in revised form 25 July 2018; Accepted 26 July 2018
Available online 21 September 2018

large fraction of the 'missing nitrogen' in N budgets (Pujo-Pay and Conan, 2003). For example, van Kessel et al. (2009) and Manninen et al. (2018) reported that, on average, DON leaching losses are equivalent to one-third of total dissolved N (TDN) losses from cultivated soil including grassland, pasture and cereals from Europe. Recently, several studies have been carried out investigating leaching of DON from soils under forest (Kiikkilä et al., 2013; Campbell et al., 2014) and grassland (Necpalova et al., 2012; Riaz et al., 2012; Hoeft et al., 2014). However, only a few studies has focused on investigating losses of DON from arable soils (Macdonald et al., 2016; Manninen et al., 2018), particularly in the Mediterranean climatic conditions. To the authors knowledge, there are few studies published to date investigating DON content on soils under Mediterranean conditions, for instance the studies carried out in plant communities in Spain (Delgado-Baquerizo et al., 2011) and vineyard in Greece (Christou et al., 2006).

Neff et al. (2003) noted that DON contains a mixture of recalcitrant and labile compounds with substantial and very different roles in terrestrial biochemistry, which may affect the N balance in soil in two ways. Firstly, it can enable a 'short-circuit' in the terrestrial N cycle whereby plants absorb some DON forms directly from the soil solution, without the need for microbial mineralisation in soil (Näsholm et al., 2009). Secondly, it may represent a significant N loss when plants and edaphic microorganisms cannot assimilate available DON in the soil solution, with some forms of DON being flushed from ecosystems during rapid N leaching (Neff et al., 2003). As mentioned above, the latter has been widely demonstrated for forest (Kiikkilä et al., 2013; Campbell et al., 2014) and grassland ecosystems (Necpalova et al., 2012; Riaz et al., 2012; Hoeft et al., 2014), but it has not been properly investigated and quantified in agricultural soils. Thus, it is important to evaluate the potential effects on DON pools and crop production caused by excessive DON leaching in agricultural soils. For instance, Ros et al. (2009) noted that after N fertiliser application to soils, changes in N flux can occur through the DON pools. However, there are still many gaps in our understanding of the significance of DON in agricultural production systems as a potential pathway for N losses (Murphy et al., 2000).

The impact of DON losses from agricultural soils on water quality has recently been shown in different studies where DON in surface waters was related to the surrounding area of agricultural land (Rasmussen et al., 2008; Bartley et al., 2012; Wohlfart et al., 2012; Evans et al., 2014). At the catchment level, agricultural fields have been linked to increase DON export (Mattsson et al., 2009), with the increase suggested to originate from intensive farming practices (Mattsson et al., 2005). Van Kessel et al. (2009) concluded that leaching of DON from agricultural soils into surface water leads to eutrophication and acidification. On the other hand, Worrall et al. (2004) noted that the removal of DOC from water sources represents one of the major costs to water treatment in large parts of Britain. Therefore, a better understanding and quantification of DON and DOC leaching from agricultural soils would help minimise its losses and effects on agricultural production and receiving water quality.

In the Mediterranean zone of Chile, there is a serious risk of diffuse pollution of surface water bodies and groundwater due to excessive applications of N fertilizers for maize (*Zea mays*) under irrigation (Fuentes et al., 2014; Corradini et al., 2015; Nájera et al., 2015). This is a particular concern in areas with coarse-textured soils, which are more prone to N leaching due to low water-holding capacity (Casanova et al., 2013). These concerns also extend to other Mediterranean climate regions of the world where irrigated maize fields with high N doses represent a high risk of creating diffuse N pollution areas (Isidoro et al., 2006; Berenguer et al., 2009; Salmerón et al., 2011; Simeonova et al., 2017).

Establishment of cover crops during the intercropping period of maize (replacing bare fallows) in these Mediterranean zones has been proposed to counteract the negative impacts of DIN leaching or diffuse pollution from irrigated maize fields (Salmerón et al., 2011; Gabriel and Quemada, 2011; Gabriel et al., 2012). However, most soils in such agroecosystems are depleted of their antecedent soil organic carbon (SOC) pool and inclusion of cover crops can enhance SOC pool and microbial activity (Lal, 2013), hence increasing the risk of DON leaching due to higher total inputs of N (van Kessel et al., 2009). Another important consideration is that cover crop species (e.g. grasses (Poaceae) or legumes (Fabaceae)) used in a crop rotation may influence the DON:DIN ratio, but their impact on DON leaching is particularly poorly understood. Moreover, because plant residues from a winter legume included as a cover crop are rapidly decomposed (Wagger et al., 1998), it is well known that this may increase SOC and organic N. There is a risk of this organic N leaching from the system if its release from cover crop residues and the N organic mineralisation is not synchronised with the N requirements of the following crop (Gentry et al., 2013).

However, the components of dissolved organic matter (DOM), DON and dissolved organic carbon (DOC) are directly associated in soil-water systems. Vinther et al. (2006) reported higher losses of DOC by leaching from cover crops than from bare soil in Denmark. Vinther et al. (2006) also noted that DOC could be an important energy source for denitrifying bacteria in deeper soil layers and thereby reduce leaching of dissolved N forms to groundwaters. In addition, there are potential effects of leached DOC on receiving water quality due to changes in the functioning of aquatic ecosystems, through its influence on light regime, energy and nutrient supply, and metal toxicity (Evans et al., 2005). There are very limited understanding and quantification of the potential effects of cover crops on cycling and losses of DON and DOC from soils under maize cultivation under Mediterranean conditions.

In this study, we examined the combined effects of inorganic N fertilisation and cover crop inclusions on nitrogen and carbon leaching loads (DIN, DON and DOC) and ratios of soluble components (DON:DIN, DON:TDN and DOC:DON) from a coarse-textured soil from Central Chile, to reduce their impact on receiving water quality across agricultural landscape in Central Chile and similar Mediterranean conditions in other places worldwide.

2. Material and methods

2.1. Experiment description

The study was conducted in a temperature-controlled glasshouse (25 °C), on undisturbed soil columns packed in PVC tubes (0.2 m diameter, 0.5 m long), at the Antumapu Experimental Station located in Santiago, Chile (33°34′S, 70°38′W). The soil was taken from the Antumapu Experimental Station and is classified as an Entic Haploxeroll (CIREN, 1996). A total of 52 (13 treatments * 4 replicates) soil columns were established and monitored over a period of August 2015 to September 2017. Each soil column had a funnel at the bottom filled with quartz sand as a filter for solid particle removal. A plastic tube connected the funnel with a plastic bottle (4 L) that collected the deep-percolating water from the soil column.

The first season with maize (spring-summer 2016) ran from October 2015 to March 2016, but samples were not taken because the soil columns were in a settling stage. After the maize was harvested (March 2016), dissolved N forms were measured from April 2016 until September 2016 (autumn-winter 1), from October 2016 until March 2017 (spring-summer 1) and from April 2017 until September 2017 (autumn-winter 2).

Table 1 summarizes the physio-chemical properties of the soil columns studied. At field level, two horizons of the soil (0–42 cm and 42–50 cm) were sampled and a composite soil sample of five constituent samples per horizon was collected for chemical and physical characterisation. They were analysed as bulk simple sample following Chilean standard methods for soil chemical (Sadzawka et al., 2006) and physical analyses (Sandoval et al., 2012), including: soil pH_{water} (1:2.5, by potentiometry and pH meter), electrical conductivity (EC_e, in soil extract with a conductivity meter), soil organic matter (SOM, by