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Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land

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ABSTRACT

Introducing cover crops in irrigated areas may play a relevant role in providing ecosystem services such as erosion control, clean water and mitigation of soil degradation. Our objective was to determine the effect of replacing the traditional winter fallow in crop rotations of irrigated semi-arid areas by a cover crop on organic C and N sequestration, aggregate stability, water infiltration, and nitrate leaching. The study was conducted comparing barley (*Hordeum vulgare* L.) and vetch (*Vicia* sp. L.) cover crops to the fallow over the course of 10 years, with most variables measured every other year. Compared to the fallow, cover crops promoted C sequestration at a rate of 180 kg C ha^{-1} $year^{-1}$ and N retention at a rate of 13 kg N ha^{-1} $year^{-1}$. By the end of the experiment, the barley cover crop had enhanced the soil structural stability, the water holding capacity, the infiltration rate and the saturated hydraulic conductivity with respect to those characteristics in the fallow, with the vetch treatment having an intermediate effect. Compared to the fallow, barley mitigated the nitrate leaching risk by reducing inorganic N content in the top 4 m of the soil profile. Improvements in C and N stocks and soil and water quality may be attained by using cover crops in degraded soils.

1. Introduction

Irrigation is one of the most relevant adaptation strategies to climate change in semi-arid areas because it increases and stabilizes productivity (Tilman et al., 2002). However, misuse of irrigated land may lead to rapid C mineralization, soil structure degradation and water pollution (Lal et al., 1989). Introducing cover crops (CC) in irrigated areas has been suggested as an economical approach to maintaining soil and water quality without reducing harvested agricultural products (Benincasa et al., 2010; Gabriel and Quemada, 2011; Salmerón et al., 2010). Cover crops replace bare fallows in crop rotations during fall or winter periods and are terminated before the subsequent main crop is sown. Used for erosion control (Lal, 2015), nutrient supply (Thorup-Kristensen et al., 2003) and nitrate leaching mitigation (Gabriel et al., 2012), CC might be a powerful tool to recover degraded soils. However, soil restoration is a slow process, and there is a need to determine the time required for CC to have a significant impact on recovering soil functionality.

Integrating CC into crop rotations presents an opportunity to increase soil C sequestration and organic matter (Poeplau and Don, 2015). Increasing soil organic C (SOC) in low organic matter soils is crucial for enhancing soil quality and affects many physical and chemical processes such as the stabilization of soil structure or plant available nitrogen (Lal, 2015). Moreover, in semi-arid climates, biomass production is low, and increasing SOC is particularly challenging. If irrigation is available, the production of biomass can be greatly increased, but the challenge of increasing SOC remains if hyper-thermic conditions cause rapid mineralization and low humification rates, as in many Mediterranean areas (Gervois et al., 2008). Consequently, soils with low SOC that have become degraded due to long periods of intensive arable cropping are often found in these regions. Soil organic matter contains nitrogen (N) as well as C, so efforts to retain SOC should be coupled with the retention of soil organic N (SON) (Powlson et al., 2011). Legume CC may play an important role by adding more atmospheric N_2 through fixation where the available N limits C sequestration. Quantitative evidence about the effect of CC on SOC and SON in irrigated systems in semi-arid areas is lacking but necessary to understand the effect of CC on the mitigation of climate change and the enhancement of soil quality.

Soil aggregation affects soil physical, chemical and biological properties and protects SOC from microbial decomposers by physical encapsulation (Blanco-Canqui and Lal, 2004). Soil aggregates are

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stabilized by various mechanisms and perform differently against external factors such as irrigation, plant cover or tillage. In turn, these management practices influence the quantity and relative stability of aggregates (Six et al., 2004). Water-stable aggregates (WSA) are good indicators of soil degradation and are crucial for the maintenance of water infiltration and the reduction in soil crusting and erodibility (Saygin et al., 2017).

Infiltration is one of the most important processes in water balance, and it determines the relative quantities of rainfall transformed into soil-available water and runoff (Abu-Hamdeh et al., 2006). In irrigated areas, low infiltration reduces water efficiency and may enhance puddle formation that limits crop growth. Cover crops that replace fallows may increase soil infiltration by enhancing SOC, WSA, and hydraulic conductivity (Angers and Caron, 1998). Differences in species effects are more controversial, and while some studies have found that grasses have the largest effect due to high C contribution (Schwartz et al., 2003), others have reported that legumes have a larger effect on infiltration (Bodner et al., 2008). Despite the known relationship between soil infiltration and soil properties, there is a lack of knowledge about the effects of different CC on soil aggregation and infiltration.

Cover crops are known for improving N recycling in the soil-plant system (Thorup-Kristensen et al., 2003). Over-fertilization is common in highly profitable, irrigated crops, and the residual soil N after the harvest is prone to leaching during the fall and winter fallows, contributing to increase nitrate pollution in irrigated areas (Isidoro et al., 2006; Quemada et al., 2013). Cover crops mitigate this process by taking up nutrients before they are washed out and retaining N in their biomass, either above or below ground. Attempts to quantify the reduction in nitrate leaching due to CC have returned notable results (Li et al., 2007; Gabriel et al., 2012); however, looking at the soil inorganic N profile in depth after a reasonable number of years may constitute solid proof of the success of the practice in reducing nitrate leaching.

The objective of this work was to determine the effect of replacing the traditional winter fallow in crop rotations of irrigated semi-arid areas with a cover crop. Specifically, we focused on the effects on organic C and N sequestration, aggregate stability, water infiltration, and nitrate leaching. In this study, CC were introduced > 10 years ago, and most of the variables were measured every other year.

2. Material and methods

2.1. The experimental site and design

The study was conducted at La Chimenea Field Station (40°03′N, 03°31′W, 550 m a.s.l.) in the central Tajo river basin near Aranjuez (Madrid, Spain) from April 2006 to November 2016. The soil is representative of a large area of irrigated crops and is mapped as *Haplic Calcisol* (WRBSR, 2014) and *Typic Calcixerept* (Soil Survey Staff, 2014). These soils are characteristic of medium river terraces, and they are very permeable and highly calcareous, with moderate organic matter content. The soil properties determined in a trench at the field site are shown in Table 1. According to the Köppen classification, the climate is cold semi-arid (BSk), with a mean annual temperature of 14.6 °C and a mean annual precipitation of 373 mm. The most important weather variables were recorded hourly throughout the experimental period with a weather station (CR23X, Campbell Scientific, Logan, Utah, USA).

Table 1
Soil properties at the beginning of the experiment.

Depth (cm)	0–20	20–40	40–70	70–120	> 120
pH (1:2.5)	8.16	8.06	8.02	7.84	7.85
EC (1:2.5, dS m^{-1})	0.31	0.45	0.90	2.19	2.16
Organic matter (g kg^{-1})	17.4	13.9	8.6	7.4	6.1
CO_3 (g CO_3^{2-} kg^{-1})	198.0	201.3	159.0	181.0	228.3
Sand (g kg^{-1})	260	250	250	250	310
Silt (g kg^{-1})	490	510	520	460	490
Clay (g kg^{-1})	250	240	230	290	200
Texture class	Loam	Silt loam	Silt loam	Clay loam	Loam

The field experiment consisted of a 10-year crop rotation, with or without a winter CC between consecutive main summer crops. A maize field planted in 2006 was divided into twelve plots (12 × 12 m^2) randomly distributed in four replicates of three treatments: barley (*Hordeum vulgare* L.) and vetch (*Vicia villosa* L. or *V. sativa* L.) as CC during the fall and winter period and bare fallow as the control. The main crops were sown during April and harvested with an experimental combiner by the end of September. The main crops were maize (*Zea mays* L.; 2006 to 2010, 2013, 2014 and 2016) and sunflower (*Helianthus annuus* L.; 2012 and 2015). In the summer of 2011, the field was fallow to finish with a maize monoculture and control weeds. Cover crops were sown by broadcasting over the main crop stubble and covered with a 5-cm shallow cultivator that passed over all the plots in the first fortnight of October. All the plots were treated with one application of 2% glyphosate in March to terminate the CC, leaving the chopped residues on the ground. The main crops were directly sown over the CC residues and irrigated by a sprinkler system according to crop evapotranspiration (Allen et al., 1998). From 2006 to 2010, all the plots received the same amount of fertilizer before sowing the main crop. The fertilizer used included 210 kg N ha^{-1} as ammonium nitrate split into two applications, 120 kg P ha^{-1} as triple superphosphate and 120 kg K ha^{-1} as potassium sulfate. Fertilization was suspended from 2010 to 2013 to lower soil nutrient stocks. In 2014 and thereafter, maize fertilization was adjusted based on available N (topsoil inorganic N at sowing plus half of the N in the aboveground CC biomass), while the fallow treatment received 170 kg N ha^{-1}, the maize after vetch received 140 kg N ha^{-1}, and the maize after barley received 190 kg N ha^{-1}. All the plots received 30 kg P ha^{-1} and 100 kg K ha^{-1}. The sunflower crops were not fertilized. Cover crops were never fertilized or irrigated.

2.2. Crop sampling

The cumulative biomass produced was calculated by adding the aboveground biomass of main crops at harvest and that of the CC at termination from each year. Weed biomass in the fallow treatment was also added in the years when it was relevant (7 out of 10). To determine the main crop biomass, the harvest index (= grain / (grain + the rest of the aboveground biomass)) was obtained in a 1 m stripe per plot and applied to the yield recorded in the experimental harvester to calculate the rest of the aboveground biomass. Cover crops and weed biomass were measured in four 0.5 m × 0.5 m squares randomly harvested from each plot before CC termination. Aboveground biomass was cut by hand at the soil level, dried, weighed, ground and saved for the analysis of total C and N concentrations in subsamples of the main crop and the CC (or weeds). The annual C input was calculated by multiplying the dry biomass remaining in each plot by its C concentration, assuming that all CC residues remained in the field, whereas most of the maize and sunflower biomass was removed from the experiment, leaving the same residue amount (≈1000 kg ha^{-1}) in all plots. Removing main crop residues from the field is practiced by about half of the farmers in the area, increasing the risk of soil degradation. The cumulative C input was obtained by adding up the annual inputs for each plot. The cumulative N fixed by the vetch was calculated by adding the N_2 fixed each year, which was the fixed atmospheric N_2 calculated by comparing the natural ^{15}N abundance in vetch and barley plants for each plot (Shearer and Khol, 1986). The N content in the CC was obtained by multiplying their dry aboveground biomass by their N concentration for each plot and year.

2.3. Soil sampling and field measurements

Soil samples were collected after harvesting the main crop every