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Including cover crops during fallow periods for increasing ecosystem services: Is it possible in croplands of Southern South America?

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ABSTRACT

The integration of cover crops (CC) into annual crop rotations improves the provision of multiple ecosystem services in time and represents an alternative paradigm to achieve sustainability goals. In spite of the benefits that several authors have exposed, CC are seldom included in rotations because their water consumption could affect cash crops development. We evaluated the possibility of including CC in the agricultural area of Rio de la Plata grasslands and identified its optimal duration depending on both environmental conditions and crop rotations. Fallow areas were located based on NDVI time series derived from MODIS satellite images and the influence of CC on the subsequent cash crop was evaluated based on modeled changes in soil water contents at the sowing date of the cash crop. Our land use classifications revealed that single crop rotations, mostly summer crops with winter fallow periods, occupy a large proportion (89%) of the agricultural portion of the Rio de la Plata grasslands studied. In most of the region, sowing CC of 3 to 5 months of length during fallow periods had little impact on soil water contents at the sowing date of the following cash crop. As expected, the optimal CC duration in the different sub-regions increased with the average rainfall occurred during the fallow period. The possibility of sowing CC without affecting cash crops yields opens the opportunity for intensifying crop sequences in the region, oriented to mitigate environmental concerns raised by monocultures and agricultural simplification.

1. Introduction

Simplification and intensification of agricultural systems (e.g. continuous agriculture and monocultures) challenges the sustainability of crop production, both at national and global scales. Several practices aimed to increase productivity affect ecosystem components and processes, disrupting numerous regulating and supporting ecosystem services, including nutrient cycling, climate and water regulation, pollination services, weed resistance and pest and disease regulation (Palm et al., 2014; Power, 2010). This trends have demanded continuous research in cropping systems where ecosystem services are preserved and production is sustained in the long-term (Foley et al., 2003; Malézieux et al., 2009; Oliver et al., 2010).

Recently, an alternative paradigm to mainstream agricultural practices has been proposed to meet the challenge of increasing productivity but maintaining the supply of ecosystem services and therefore achieving sustainability goals. This, "ecological intensification" paradigm proposes the use of ecological principles to guide the management of agricultural systems for increasing both provisioning services (e.g. food, fiber) but also regulating, supporting and cultural ecosystem services (Tittonell, 2014). Under this view, it has been suggested that trade-offs between agricultural production and ecosystem services can be avoided and that 'win–win' scenarios are possible. Examples of ecological intensification include organic agriculture, diversified farming systems, nature mimicry and some forms of conservation agriculture (Tittonell, 2014). Practices such as intercropping, double cropping or cover crops have been proposed in conservation agriculture to increase sustainability (Bommarco et al., 2013; Doré et al., 2011), because several works show that the integration of cover crops into annual crop rotations improves the provision of multiple ecosystem services in time, such as N regulation, soil aeration, weed and pest control, etc. (Schipanski et al., 2014). Moreover, the reduction of fallow periods allows mimicking the functioning and structure of natural systems and therefore reducing the environmental impacts of agricultural land use changes (Jackson and Jackson, 1999).

A large body of knowledge is being rapidly developed on cover

Abbreviations: SWCsd, soil water content at the cash crop sowing date; PSWCsd, probability of finding the same SWCsd after fallow

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crops and their impacts on agricultural systems. Several authors have studied how to improve structural and functional attributes of agroecosystems by sowing Cover Crops (CC). The inclusion of CC generally increases soil organic matter (Ding et al., 2006; Duval et al., 2016; Sainju et al., 2006; Venkateswarlu et al., 2007) and improves physical properties (Chen et al., 2014; Hermawan and Bomke, 1997; Sasal and Andriulo, 2005; Varela et al., 2011). Moreover, CC could improve nutrient cycling through the inclusion of N-fixing legumes, decreasing leaching by nutrient immobilization through grasses or resorting to both methods simultaneously (Bergkvist et al., 2011; Büchi et al., 2015; Kramer et al., 2002; Plaza-Bonilla et al., 2015; Rosecrance et al., 2000; Sainju et al., 2005; Teixeira et al., 2016). In general, single cash crops use only a small proportion of potentially available resources (Caviglia, 2004). Thus, shortening fallow periods with CC could be useful to increase capture and resource use efficiency (e.g. radiation and water) in order to increase ecosystem services.

In spite of the benefits exposed, CC are seldom included in rotations because their water consumption could affect cash crops development. Soil water content (SWC) at the cash crop sowing date (SWCsd) is a good variable to evaluate this effect. Restrictions in cash crop development due to water availability do not occur if SWCs remains unchanged (or increases) after fallow periods. Both locally and globally, different effects of CC in SWC have been found, depending on the length of fallow period (or CC duration) and precipitation regimes. Some authors found that CC lead to a significant decrease in SWCsd as compared to bare soil fallow periods but with a small impact on cash crops yields (Nielsen and Vigil, 2005; Restovich et al., 2012; Rimski-Korsakov et al., 2015). Other authors even propose that SWCsd may increase, because soil evaporation decreases due to increased soil cover and mulching (Quiroga et al., 2005). In summary, the potential effect of CC on SWCsd will depend on environmental conditions and CC duration (Verburg et al., 2012).Therefore, mapping fallow periods and their duration, as well as environmental conditions is key for potentially including CC of different durations into current crop rotations.

Several regions of the world lack crop or vegetation cover during part of the year, allowing fallow periods of different duration and offering opportunities for including CC (Siebert et al., 2010). The *Rio de la Plata* grasslands (including the *Pampas* of Argentina and *Campos* of Uruguay and Brazil), is one of the world's largest croplands where accelerated land use changes are challenging the sustainability of crop production and food security worldwide. During most of the twentieth century traditional cropping systems of the *Rio de la Plata* grasslands included perennial pastures in similar proportions to annual crops (García-Préchac et al., 2004; Hall et al., 1992; Soriano et al., 1991). However, since the 90s, cropland area has increased at the expense of a reduction in pastures area (Baldi and Paruelo, 2008; Viglizzo et al., 2011). Furthermore, cropping sequences became simpler, with a predominance of soybean and limited crop diversity, raising concerns about the sustainability and environmental risks associated to crop production in a region which is relevant for the world grain and oil market (FAO, 2014). Currently, a large proportion of the agricultural area of the *Rio de la Plata* grasslands is potentially under fallow periods at some time during the year (either during summer or winter) (Paruelo and Guerschman, 2005; Restovich et al., 2012). However, there is no detailed information on their spatial distribution or interannual variability, because National agricultural statistics (http://www.siia.gov.ar/sst_pcias/estima/estima.php) and National Census (http://www.indec.gov.ar/cna_index.asp), only report single crop areas, and do not report areas under fallow or double crops.

Satellite images can be used to determine changes in agricultural land uses and therefore help identifying fallow periods location and duration (Baeza et al., 2014; Kerr and Ostrovsky, 2003). Different wavelengths are recorded by sensors on board satellites that can describe biophysical properties of ecosystems (Myneni et al., 1995). The Normalized Difference Vegetation Index (NDVI) is a widely used index, which integrates two key aspects of the spectral behavior of photosynthetic tissues: low reflectance in red wavelengths and high reflectance in the near infrared portion (due to chlorophyll absorption and leaf mesophyll structure, respectively) (Myneni et al., 1995; Paruelo, 2008). NDVI has been related to leaf area and thus used to describe crops phenology based on images time-series (Sakamoto et al., 2010). Several authors used this approach to perform land use classifications, identifying different crop types and fallow periods (Friedl et al., 2002; Guerschman et al., 2003; Han et al., 2008; Siebert et al., 2010; Wardlow et al., 2007).

Our objective was to evaluate the possibility of including CC in the agricultural area of *Rio de la Plata* grasslands and to identify its optimal duration depending on both environmental conditions and crop rotations. To achieve this objective, we: (1) spatially identified fallow periods and classified them into winter or summer fallows; (2) determined sub-regions with a similar proportion of summer, winter or double crops; and (3) evaluated soil water content on the cash crop sowing date (SWCsd) after fallow periods or after CC with different durations within each sub-region.

2. Materials and methods

2.1. Study area

Our study area covers most of Rio de la Plata grasslands in Argentina and Uruguay (Soriano et al., 1991). This huge region has more than 120 million hectares and extends between 30° and 39° south latitude parallels and 50° and 66° west longitude meridians. It represents the agricultural central area of Argentina and west coast of Uruguay (Fig. 1). In this region field crop production has increased since the last quarter of the 19th century and nowadays is the key agricultural activity in the region, with the widespread use of no-till farming, agrochemicals and transgenic crops. Currently, soybean is the main crop in the region, followed by maize, wheat, sunflower and other minor crops (FAO, 2014).

The region is a vast plain with a warm and temperate climate. Rainfall occurs throughout the year, decreasing from north to south and east to west from 1200 to 600 mm annually (Cabrera, 1976). Rainfall has a seasonal pattern with a summer maximum and lower amounts of precipitation in spring and autumn, with a minimum in winter (Hall et al., 1992). The high variability of rainfall events is mainly explained by the ENSO phenomena (Podestá et al., 2002). Mean annual temperature varying from 17 °C in the north to 14 °C in the southern portion of the region, being 6 to 8 °C higher in summer and about 5–6 °c less in winter (Hall et al., 1992). Soils are mainly based on loess "Pampeano" deposits, with high proportions of silt and high natural fertility. Dune ripples, sandy soils and loosely structured surface horizons predominate in the west wile silt and clay textured soils are common in the central and eastern Buenos Aires. In Entre Rios and Uruguay (northeast of the study area) soils are predominantly clay-rich (Vertisols) with a highs water erosion risk and low drainage (Panigatti, 2010; Soriano et al., 1991).

2.2. Evaluation of the inclusion of CC in fallow periods

We evaluated the possibility of including CC in the agricultural area of Rio de la Plata grasslands and identified their optimal duration by means of three steps. First, we used temporal-series of MODIS sensor to identify spatially fallow periods and classified them into winter or summer fallows in the 2001–2010 period. Second, we delimitated different sub-regions that had similar proportions of winter, summer and double crops to analyze the variation of the area occupied by fallow periods along the same period. And third, we performed water balances using both climatic and soil characteristics found in different weather stations located in each sub-region. From these water balances, we evaluated the probability of finding the same SWCsd after fallow or after CC with different durations within each sub-region. Finally, we