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# A historical perspective on soil organic carbon in Mediterranean cropland (Spain, 1900–2008)

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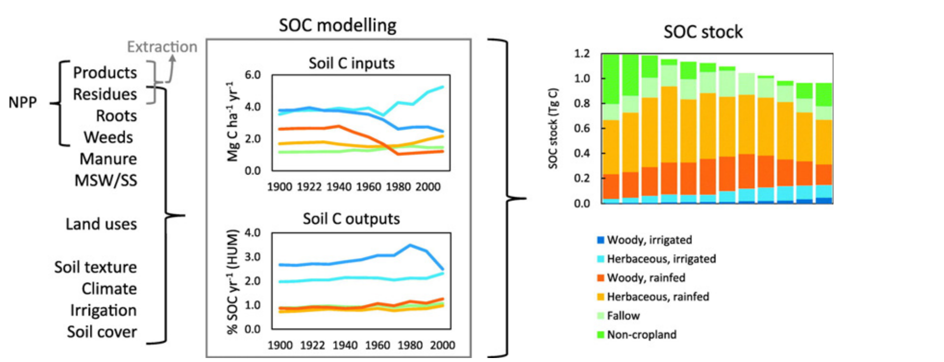
## HIGHLIGHTS

- Long-term land use, management and climate impacts on cropland SOC were modeled.
- Historical data and literature coefficients used to estimate NPP and soil C inputs
- Continuous cropland SOC declines along the studied period.
- Major drivers of SOC loss shifted from land use, to management to climatic changes.
- High impact of weed declines on SOC in woody crops; mixed effects of irrigation.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Soil organic carbon (SOC) management is key for soil fertility and for mitigation and adaptation to climate change, particularly in desertification-prone areas such as Mediterranean croplands. Industrialization and global change processes affect SOC dynamics in multiple, often opposing, ways. Here we present a detailed SOC balance in Spanish cropland from 1900 to 2008, as a model of a Mediterranean, industrialized agriculture. Net Primary Productivity (NPP) and soil C inputs were estimated based on yield and management data. Changes in SOC stocks were modeled using HSOC, a simple model with one inert and two active C pools, which combines RothC model parameters with humification coefficients. Crop yields increased by 227% during the studied period, but total C exported from the agroecosystem only increased by 73%, total NPP by 30%, and soil C inputs by 20%. There was a continued decline in SOC during the 20th century, and cropland SOC levels in 2008 were 17% below their 1933 peak. SOC trends were driven by historical changes in land uses, management practices and climate. Cropland expansion was the main driver of SOC loss until mid-20th century, followed by the decline in soil C inputs during the fast agricultural industrialization starting in the 1950s, which reduced harvest indices and weed biomass production, particularly in woody cropping systems. C inputs started recovering in the 1980s, mainly through increasing crop residue return. The upward trend in SOC mineralization rates was an increasingly important driver of SOC losses, triggered by irrigation expansion, soil cover loss and climate change-driven temperature rise.



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## 1. Introduction

Carbon (C) dynamics in cropland soils is a hot topic in Mediterranean agriculture in the context of climate change. On the one hand, soil organic carbon (SOC) is highly sensitive to management practices in these environments (Aguilera et al., 2013), and soil C sequestration can offset a large share of the full life cycle greenhouse gas (GHG) emissions of crop production (e.g. Bosco et al., 2013; Aguilera et al., 2015a, 2015b; Guardia et al., 2016). On the other hand, Mediterranean cropping systems are characterized by low SOC levels, resulting particularly vulnerable to climate change (Zalidis et al., 2002; Iglesias et al., 2011). This last condition stresses the need for increasing SOC levels to improve soil quality and fertility (Diacono and Montemurro, 2010).

Global cropland area expanded about 4-fold since 1700, up to ca. 20% of the vegetated area (Pongratz et al., 2008). In parallel, agroecosystems intensified to meet increases in population density (Ellis et al., 2013), culminating in a radical socio-metabolic transformation, with the transition from traditional organic, solar-based systems to industrial, fossil fuel based systems (Krausmann et al., 2008). The former usually operated at the local scale, relying on solar fluxes and internal biomass recycling as sources of energy and fertility. The latter are intensified through imports of fossil fuel-based industrial inputs and international or interregional trade to optimize the conditions for commodity production in a context of a global market economy (Guzmán and González de Molina, 2017; Gingrich et al., 2017). These structural characteristics shape the C cycle through effects on the type and quantity of soil C inputs and on the biotic and abiotic factors controlling C losses. Soil C inputs can potentially increase with industrialization due to a higher overall biomass production and a lower use of crop residues for animal feeding (e.g. Wiesmeier et al., 2014). Modern crops, however, usually have higher harvest indices, which reduces the production of residue relative to the main product (Johnson et al., 2006). In addition, weed biomass is more effectively suppressed in modern cropping systems (Guzmán et al., 2014), and root growth in relation to aerial biomass is usually reduced (e.g. Chirinda et al., 2012). SOC mineralization is also affected by the changes in management practices such as tillage, irrigation and fertilization (Sainju et al., 2013; Shang et al., 2015).

Along with historical management changes, SOC dynamics are affected by shifts in environmental conditions associated to global change, particularly temperature increase, which would boost litter decay (Gregorich et al., 2017) and SOC mineralization (Davidson and Janssens, 2006), potentially representing a positive feedback to climate change. On the other hand, possible reductions in precipitation in Mediterranean areas (Giorgi and Lionello, 2008) could increase water limitation of SOC mineralization.

SOC dynamics in modern conventional systems have been often compared to those of modern organic and/or low-input systems (Gattinger et al., 2012; Aguilera et al., 2013). However, specific studies on traditional organic cropping systems are very scarce, particularly at large spatial scales. Most large-scale assessments of SOC dynamics are based on crop-soil process-based simulations, validated with soil and yield data from databases such as EUROSTAT or FAOSTAT (e.g. Ciais et al., 2010; Bondeau et al., 2007). Most of these databases do not provide data before mid-20th century, or specific information on many management practices, a problem that can be overcome in studies covering smaller areas with better statistical information (e.g. Parton et al., 2015).

Spanish agriculture experienced vast technological and structural changes along the 20th century. During the second half of the century, there was a large increase in land and animal productivity, which was used to feed an increasing population, to increase the share of animal products in the diet, and to raise exports of high-value crop products (Lassaletta et al., 2014; Soto et al., 2016). Recent assessments have shown some of the biophysical costs of these productivity gains. The reliance on external and total energy consumed led to a significant decrease in the energy return on investment (EROI) (Guzmán et al., 2017), a growing dependence on feed biomass imports (Soto et al., 2016), a large nitrogen (N) surplus (Lassaletta et al., 2014) and a strong pressure on scarce water resources (Duarte et al., 2014). The main aims of this study were to analyze cropland SOC dynamics in Spain, used here as a model Mediterranean country, in the long-term (+100 years), and to identify the main drivers responsible for the observed trends. The specific objectives were: (i) to build and test a simplified SOC model for its use in historical studies; (ii) to reconstruct NPP and soil C inputs from 1900 to 2008; (iii) to simulate SOC stock changes from 1900 to 2008; and (iv) to test the sensitivity of the model outputs to changes in key model parameters.

## 2. Methods

### 2.1. Study site characteristics

Climate in Spain is mostly Mediterranean, with hot, dry summers and wet, mild autumns and winters. Severe water deficit during the summer (Fig. 1a) is one of the features controlling crops distribution and management. There is a strip of temperate climate in the northern coast, and a gradient of dryness towards the South-East (Fig. 1d).

Annual mean precipitation during the 20th century in Spain ranged from 500 to 900 mm, with no clear trend (Fig. 1b). Mean temperature increased from 12.3 °C in the 1900–1909 period to 13.8 °C in the 2000–2002 period (Fig. 1c, e, f), corresponding to an average increase rate of 0.17 °C per decade, which can be compared to the 0.1 °C decadal average global land warming estimated for the 1901–2012 period (Hartman et al., 2013). These changes have resulted in increasing drought severity during the last 50 years (Vicente-Serrano et al., 2014).

The main soil orders in Spain are Entisols and Inceptisols, which account for more than three-quarters of the total national surface area (Gómez-Miguel and Badía-Villas, 2016). National means and standard deviations (in parenthesis) for pH, soil organic matter, and sand, silt and clay proportions (%) are 7.47 (1.49), 2.53 (2.87), 51.77 (19.99), 26.50 (14.73) and 21.77 (10.98), respectively (López Arias and Grau Corbí, 2005).

Area and production values for each crop type-management category were retrieved from the Agricultural Statistics Yearbooks, available online at MAPAMA (2017). In some cases, area and production values in rainfed and irrigated land had to be adjusted to match the total values provided in the source and the total irrigated area. Outliers in the data were also disregarded. The estimation of the total irrigated area and the segregation of the irrigated area by irrigation types was based on various official reports (MAICOP, 1904; MF, 1918; MAGRAMA, 2015) and secondary sources (Calatayud and Martínez-Carrión, 2005). Cropland area increased from 33% in 1900 to 41% in 1970, decreasing down to 34% by 2008 (Fig. 2a). Herbaceous crops represent the majority of cropland area (Fig. 2a), but the share of woody crops is also very significant (ranging from 18% in 1900 to 28% in 2008). Fallow land was highest in 1960 (36% of herbaceous crops area), and lowest in 2000 (24%). Irrigated area increased from 6% to 19% of cropland from 1900 to 2008, with a growing share of sprinkler irrigation systems since 1970 and of drip irrigation systems since 1990 (Fig. 2b, c).

### 2.2. Soil organic carbon model description

Humified Soil Organic Carbon (HSOC) model is an adaptation of RothC model (Coleman and Jenkinson, 1996), consisting in its simplification into two active SOC pools; fresh organic matter, (FOM) and humus (HUM), and one inactive pool (IOM) (Fig. 3). In HSOC model, the three labile C pools in RothC (resistant plant material, decomposable plant material, and microbial biomass) are merged into a single pool (FOM). This allows for the reduction of internal feedbacks and thus for an easier interpretation of the model functioning. The simplification of the model also allows for a better integration of factors that have an