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Research Article

C-sequestration and resilience to future climate change of globe artichoke cropping systems greatly depends on crop residues management

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Abstract

Globe artichoke is one of the most intensively cultivated horticultural species in Mediterranean regions. In this context, sustainable agronomic management is a requisite to increase the soil carbon content, making the artichoke cultivation system more resilient to climate change. A ten-year experiment was considered to forecast the influence on soil C dynamic of three globe artichoke managements: monoculture with dry crop residues incorporation (conventional monoculture); monoculture with the inclusion of a cover crop (alternative monoculture); rotation with cauliflower plus cover crop (biannual rotation). During the 2006-2016 period, total soil organic carbon content and plant C inputs to soil were measured. RothC model was used to predict the effect on the soil C stock and C sequestration potential in 20 years of the three managements tested in the field, plus a hypothetical conventional scenario with no residues' incorporation (no-residues). Plant C inputs increased according to the number of crops in rotation in each system, resulting 25% lower in conventional monoculture with respect to biannual rotation, whereas the C stock change was significantly higher ($p<0.01$) in conventional and alternative monoculture (+ 7.57 and 7.14 t C ha^{-1}) compared to biannual rotation (-1.03 t C ha^{-1}). In the twenty years predictions all the systems had a positive C balance. The soil organic carbon change (t C ha^{-1}) for the future climate was + 7.2 for alternative monoculture, and + 0.6 for monoculture with residues removals. For the first time, in this study, we clearly shown in the long-term and in a climate change perspective that an improper crop residues management might lead to a loss of soil fertility in intensively cultivated horticultural soils under Mediterranean climate. The adoption of biannual rotation with cauliflower needs to be evaluated carefully because it proved to be less efficient in terms of C sequestration potential.

Keywords: *Cynara cardunculus* var. *scolymus*, crop modeling, soil carbon content, sustainable horticulture

1. Introduction

In view of wellbeing, World Health Organization directions advocate an enhancement in vegetable individual daily intake. Therefore, worldwide vegetable production is quickly increasing (FAO 2017). Vegetable production is predominantly achieved through intensive horticultural systems. High rates of chemical inputs (e.g. fertilizers, pesticides), repeated cultivation operations, and inadequate soil surface cover are frequent issues threatening the preservation of soil quality (organic matter content and other soil properties) in intensive horticultural systems (EIP-AGRI Focus Group 2015). Moreover, the high application of chemicals also increases the probability that fertilizers and pesticides reach surface and groundwater by runoff and leaching (Eurostat 2015). Soil health is somewhat impaired by intensive agriculture, primarily for fertility depletion (e.g. soil organic matter). For some horticultural crops, only a small amount of organic material is returned to the soil after harvest (Brennan and Acosta-Martinez 2017). Thus, horticultural cropping systems could have a serious negative effect on soil fertility and ecosystem services delivery. Indeed, within the Mediterranean intensive horticultural systems, the distribution of organic fertilizers based on humic and fulvic acid has become a common practice, in relation to the need to improve cation exchange capacity of the soil and provide slowly available organic nitrogen (Alvarenga et al. 2015; Urra et al. 2019). At present, agronomic studies have usually neglected investigations on soil fertility in horticultural systems, and this may be regarded as an important research shortcoming, which should be addressed with the aim to develop new knowledge to meet the demand of sustainable food by a rising population (Norris et al. 2018). To improve soil fertility, different alternative managements and agronomic techniques have been suggested, aiming also at reducing external inputs and nutrients losses, e.g. stubble retention. Sustainably managed, agriculture can minimize the impacts caused by intensification and foster the soil resilience in the long-term (Gomiero et al. 2011). Over the past years, research has resulted in significant progress in developing techniques/practices of crop production while reducing negative effects on soil quality and ecosystem services delivery, i.e. adopting conservation agriculture with minimum tillage, and decreasing exogenous fertilisers application by a sound use of crop rotations or pre-plant soil analysis (Knowler and Bradshaw 2007). Nevertheless, these progresses were mainly addressed to open-field crops such as cereals, mostly used for animal feeding (Cassidy et al. 2013) rather than to human consumption. To enhance soil organic carbon (SOC) content and promote sustainability, an adjustment of management is needed, including organic amendments both of animal and of plant origin, cover-crop or mulching, and a lower number of cultural operations (EIP-AGRI Focus Group 2015). Globe artichoke (*Cynara cardunculus* L. var. *scolymus* (L.) Fiori) is a horticultural species widely grown in Mediterranean climate-type areas for its heads (Deligios et al. 2017). In Southern Italy, where the majority of the globe artichoke cultivation is carried out, re-flowering genotypes (e.g. Spinoso sardo) are well adapted to forcing techique (summer implantation by dormant offshoots, followed by frequent irrigations) and are usually cultivated in monoculture (consecutively for seven or more years), with a large amount of chemical fertilizers supply (e.g. 250 – 400 kg N ha^{-1}, Bianco and Calabrese 2009). The earliest head productions of such genotypes (from October to February), because of their better quality and higher commercial price, are destined for fresh consumption, while only the late ones (from late March to April) are used for the food industry (Sgroi et al. 2015).

From this perspective, an environmentally sound management, including incorporation of crop residues, use of cover-crop, and a proper crop-rotation can be regarded as practices able to ensure long-term nutrient supply and soil fertility. Furthermore, these techniques may be considered as management alternatives on which to plan innovative and resilient globe artichoke cropping systems.

To promote alternative management of artichoke cropping systems, is of paramount importance to enhance awareness of farmers and policy makers on advantages of an environmental sound crop management. The adoption of more resilient cropping systems, aims to positively affect the soil C stock, contributing significantly to adaptation and mitigation of climate change. However, providing advices on best practices to reach the objective of increasing soil C content in soils is challenging, due to the slow change of soil C in response to management (Mondini et al. 2012), often difficult to measure in short-term field experiments. The combination of long-term experiments (> 6 years) and process-based models has proved to be an effective approach to predict the soil carbon dynamics over long periods, thus allowing for a long-term estimation of farming practices effects on SOC. Among the most used models, RothC (Coleman and Jenkinson 1999) has proved to be well suited to simulate accurately the soil C dynamics in several pedoclimatic situation and in Mediterranean cropping systems (Mondini et al. 2012; Pardo et al. 2017; Farina et al. 2018). With specific regards to horticultural systems in the Mediterranean region, a successful example of combining data from long-term experiments and process-based model, is represented by the use of RothC with a dataset obtained from an Italian long-term horticulture experiment under organic management (Farina et al. 2018). We used a long-term field experiment (Deligios et al. 2017) as a case-study representative of horticultural systems in the Mediterranean area to predict the long term effect on soil C dynamic of alternative artichoke cropping system management, namely: conventional monoculture with residue retainment in the field and improved management of fertilization, alternative monoculture with bean as cover crop and biannual rotation with cauliflower and pea as cover crop. Soil C content during the years and plant C inputs to soil were measured. For the first time, RothC model was used to forecast the long term effect of the different management combinations plus a hypothetical monoculture with residues removal scenario on the soil C stock in 20 years, used as a reference systems, but also realistic because it takes into account the still used practice of burning biomass or the possible alternative use of residues as a feedstock for biorefinery (D'Avino et al. 2020). The resilience of each system, in terms of C sequestration potential, to climate change was assessed.

Here Figure 1 The two phases of the biannual rotation system. The picture on the left shows the cauliflower phase, and the picture on the right the globe artichoke phase. In the biannual rotation management globe artichoke is grown in sequence to cauliflower. By contrast, in the traditional globe artichoke cultivation practice globe artichoke is grown in monoculture for many consecutive years.

2. Material and Methods

2.1 Site and treatments description

The long-term field experiment is ongoing since 2006 at the experimental farm 'Mauro Deidda' few kilometers apart from Sassari, in Sardinia (Southern Italy: 40°46'N, 8°29'E). Following the Köppen-Geiger climate classification (Beck et al. 2018), the experimental site has a hot- summer Mediterranean climate, with warm winters, hot and dry summers, and with the highest precipitation in autumn and winter. During the studied period (2006–2016), the mean annual temperature, precipitation and potential evapotranspiration were 16.6 °C, 529 and 776 mm respectively. The soil is Lithic Xerochrept (USDA 1999) developed on a limestone bedrock with 49.0% sand, 24.3% silt and 19.6% clay (sandy clay loam). In 2006, at the start of the experiment the topsoil (0–20 cm) soil organic C content ranged from 49.8 t ha^{-1} to 58.2 t ha^{-1}, and pH was 7.9. A full description of long-term experiment is detailed in Deligios et al. (2017). Globe artichoke, 'Spinoso sardo' varietal type, was grown according to three different crop managements: a conventional monoculture, and two sustainable systems (alternative monoculture and biannual rotation). The experimental field (in total 4080 m^2) was organized according to a randomized block design with three treatments and three replications. Blocks and plots were separated by approximately 3 m.

To mimic the traditional forcing technique (Ledda et al. 2013), every year since 2006, after plowing at 25 cm depth and harrowing at 10 cm, at beginning of July, the 10-cm-long semi-dormant offshoots of Spinoso sardo artichoke were planted. The distance between plants within a row was 70 cm, achieving a density of around 9500 plants ha^{-1}. Drip irrigation of approximately 300 mm was applied to the entire experimental field (when accumulated daily evaporation reached 35 mm, 100% of maximum evapotranspiration) from the date of planting to the first rainfalls (on average from the end of July to the end of October).

The conventional monoculture was carried out according to the ordinary practice of local farmers, incorporating into the soil the senescent artichoke residues, at the end of the growing cycle in June, by chopping, plowing and harrowing up to a 10-cm depth. Fertilizer application, based on crop uptake which reflects the synchronization of crop nutrient requirements and soil macronutrient supply (Piras, 2013) was 150, 125, and 140 kg ha^{-1} of total N, P, and K, respectively in four split doses, namely at planting, mid-September, late-November, and late-February. Pest and disease controls followed the Best Management Practices recommended at Regional level.

In the alternative monoculture, the artichoke crop cycle was ended when the harvest of heads was no longer profitable (around the first half of April) and the artichoke whole fresh residues were incorporated into the soil by chopping and harrowing at 20-cm depth. Thereafter, a bean cover crop (*Phaseolus vulgaris* L. cv. Bronco) (Monsanto Agricoltura Italia SpA, Italy) was sown, and its growing cycle was interrupted soon after the first pod harvesting to incorporate fresh residues of the cover crop before preparing the seed-bed (by plowing at 25-cm depth and harrowing at 10 cm) for the following artichoke growing cycle.

In the biannual rotation system, a two-year rotation artichoke-cauliflower (*Brassica oleracea* L. var. *botrytis*; cv Nautilus) (Clause Italia SpA, Italy) was set-up on alternate plots; thus, all phases of the crop sequence were present in the field every year. Moreover, each year in February, in inter-row spaces, a pea cover crop (*Pisum sativum* L.; cv Attika) (Limagrain Verneuil Holding, France) was systematically sown after an interow rotary harrowing pass (10-cm depth). At the end of the harvest period, both for cauliflower and globe artichoke, all fresh residues, including those of the cover-crop, were chopped and incorporated into the soil by rotary-harrowing at 20-cm depth. Two months after incorporation, the beds in all plots were plowed at 25-cm depth and harrowed at 10 cm for the next cauliflower or artichoke production cycle. In the two sustainable systems, plant nutrients demand was satisfied by the plant fresh residues incorporated to soil, since the aim was to design a cropping system without external chemical fertilisers input. Morever, the alternative monoculture and biannual rotation systems were conducted without synthetic pesticide use.

2.2 Samplings and analysis

Soil samples at 0-20 cm depth were randomly collected in July 2006 in the whole experimental field, in order to assess the total organic carbon at the start of the experiment. In the years 2009, 2013, 2016 four soil samples per plot were collected before the starting of each new growing season, in order to quantify the effect of plant residues soil incorporation (namely globe artichoke, weeds, cauliflower and cover crops). Soil samples after air-drying to constant weight, were analyzed for total organic carbon using the LECO analyzer (628 Series; LECO Corp., St. Joseph, MI, USA).

Every year, before the end of the growing season, samples of total fresh biomass were taken for each plot as follows: three plants of artichoke (for all the cropping systems); six plants of cauliflower (biannual rotation) and bean (alternative monoculture); 0.5-m^2 of central area in the inter-row spaces for the determination of pea (biannual rotation) and weeds biomass (for all the cropping systems). The average total biomass per plant was multiplied by crop density for absolute biomass (kg ha^{-1}) estimation.

Plant samples were fractionated into two parts. One part was dried at 55 °C to constant weight and stored for nutrient analysis; another part was dried at 80°C for 24 hours (up to weight stabilization) for the determination of the dry matter content. All the organic biomass utilized as C input was analyzed for C content using a LECO analyzer by a dry combustion method. Total carbon content per hectare of biomass was calculated by multiplying the content by the whole biomass value (dry-weight basis). Root biomass was estimated as 30% of the aboveground biomass for all the crops.

2.3 Modeling

The RothC model (Coleman and Jenkinson 1999) simulates SOC dynamics and has been tested in a large range of pedoclimatic conditions and cropping system management. The model requires relatively easily available inputs and produces reliable and accurate simulations (Francaviglia et al. 2012; Farina et al. 2018; Robertson and Nash 2013). Soil C is split into five pools: four active compartments, decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM), each decomposing by a first order kinetics and specific decomposition rate (years^{-1}), and one inert organic matter pool (IOM). All C inputs, from plants or external organic fertilizers, are split between DPM and RPM, with a variable ratio depending on the type of material. Both DPM and RPM decompose to form CO_2 (lost from the system), BIO and HUM, depending from soil clay (Coleman and Jenkinson 1999).

2.3.1 Running RothC

Running RothC requires the following:

(a) Climatic data: Monthly rainfall (mm), potential evaporation (mm) and mean air temperature (°C);

(b) Soil data: Clay content (%), initial SOC (t C ha^{-1}), bulk density (g cm^{-3}), depth of the soil layer considered (cm);

(c) Land use and land management data: Soil cover (1/0), C input from plants, residues, and organic fertilisers (t C ha^{-1}).

For RothC running, the potential evapotranspiration (ET) was calculated from measured weather data using the Thornthwaite equation. The irrigation amount was calculated by the difference between rainfall and ET and slightly corrected in order to keep available water at 80% during the irrigation period (from July to November) (350 mm as average). The bulk density, used to transform mg of C per kg of soil in t C ha^{-1}, was the average of the measurements in all plots at the beginning of the experiment. RothC was initialized using the SOC content measured at the beginning of the experiment using the default partitioning among the SOC pools. The model was run iteratively to equilibrium (10.000 years) in order to generate the input required to match the initial stock of SOC, and then calibrated with the conventional treatment. The aboveground C inputs of the artichoke and weeds were measured, whilst belowground were estimated according to Raccuia and Melilli (2010) for artichoke and Farina et al.

(2018) for cover crops, cauliflower and weeds considering a root:shoot ratio of 0.3. The total C input was divided into monthly fractions according to the crop phenological stage following Raccuia and Melilli (2010), ranging from a fraction of 0.05 at crop establishment to a 0.35 one at maximum biomass development.

The model was calibrated using the conventional monoculture treatment and included the modification of artichoke residues partitioning coefficient of the pools DPM and RPM, by adjusting the relative rate to fit the measured C changes in the soil (Heitkamp et al. 2012). All the other treatments were used to validate the model, with 18 pair of data (measured and modeled), not considering the data used for initialization and calibration, according to the different land management.

2.3.2 Predictions of C sequestration potential in the medium term (20 years) for the different systems

We run the model for the different cropping systems to assess the medium-term potential to accumulate soil C, using averaged field data for C inputs, irrigation and soil cover and climate projection (baseline and future climate scenarios). Twenty years of simulated weather data were obtained by AGRI4Cast Resource Portal (https://agri4cast.jrc.ec.europa.eu/DataPortal/), consisting in daily weather data for Europe (on a 25 × 25 km grid) by three General Circulation Models: (1) METO-HC (METO); (2) DMI-HIRHAM5-ECHAM5 (ECHAM); and (3) ETHZ-CLM-HadCM3Q0 (ETHZ) of the MARS-AGRI4CAST as *Daily weather data for crop modelling over Europe derived from climate change scenarios* (available at https://agri4cast.jrc.ec.europa.eu/DataPortal/, last accessed the 28th December 2020). The model was run with the baseline (1990-2010) and future (2011-2030) climate projections, obtained by each of the three General Circulation Models. Projected baseline weather data were comparable with those measured in the long-term. The temperature and rainfall changes in future climate scenarios compared with current situation were as follow: METO no change of temperature and + 13% of rainfall; ECHAM +0.35°C and +7% rainfall; ETHZ +0.6°C and +13% rainfall.

In addition to the simulations of the cropping systems tested in the field, we run also a hypothetical reference system of conventional artichoke with residues removed from the field (monoculture with-residues removals), representing a realistic situation where artichoke residues are burnt or removed as biomass for biorefinery utilization. The C inputs used to run this scenario were the same of the conventional monoculture for weeds and artichoke roots, wheareas we assumed that 75% of the artichoke aboveground biomass is removed, whatever the use, based on data reported by D’Avino et al. (2020) in a similar system. Inputs for the biannual rotation are reported as average of the two fields. Irrigation was not modified under future climate, to simulate a condition very common in Italy where farmers have normally a fixed amount of water (350 mm in our case) distributed by the Water Use Associations (Consorzi di bonifica). The resilience to future climate change of each cropping system is expressed as change in C sequestration potential i.e. % difference between SOC change in 20 years between baseline and future climates.

2.4 Analysis of data

In order to detect significant differences among systems in terms of C input to the soil and changes in soil organic C stock, data were first tested for homogeneity of variances (Bartlett's test) and for normal distribution (Shapiro–Wilk test). Data that violated the assumptions for analysis of variance or t-test were subjected the non-parametric Kruskal–Wallis test (instead of analysis of variance) or Mann–Whitney U-test (instead of the t-test). All statistical tests were performed using SAS software (SAS v 9.2 1999).

C sequestration potential of the different systems in the field and after 20 years of simulation were indicated as C stock change and obtained as:

C stock change= Cfinal-Cinitial

Where *Cfinal and Cinitial* are the SOC measured/simulated after 20 years and at beginning of experiment or simulation respectively.

To assess the model performance and to compare measured and simulated values, we used the following indicators:

i) RMSE (root mean square error),

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \mathrm{O_i})^2}{n}}$$

ranging to 0 to positive infinity, that indicates the accuracy of simulations. A value of 0 would indicate a perfect fit of the modeled data to measured. RMSE is expressed in the same unit of the measured data;

ii) coefficient of determination (R^2) of the linear regression estimates versus measurements (association), ranging from 0 (absence of fit of the regression line) to 1 (perfect fit of the regression line): the closer the values are to 1 the better the model performance;

$$\mathrm{R}^2 = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \mathrm{O_i}) \cdot (\mathrm{O_i} - \overline{\mathrm{O}})}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \overline{\mathrm{P}})^2 \cdot \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i} - \overline{\mathrm{O}})^2}}$$

iii) the EF (model efficiency) with a range from negative infinity to 1 (optimum), the closer the values are to 1 the more efficient the model with respect to the observed mean

$$\mathrm{EF} = 1 - \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{P_i} - \mathrm{O_i})^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{O_i} - \overline{\mathrm{O}})^2}$$

where, P_i and O_i are the i^{th} simulated and observed values respectively, $\overline{\mathrm{P}}$ and $\overline{\mathrm{O}}$ the average simulated and observed values respectively, and n the total number of observations.

3. Results and discussion

3.1 Crop residues, C inputs and soil C stock change in the field experiment

Cumulative C inputs for the three crop management systems tested in the field are shown in Table 1.

Here Table 1 Mean cumulative carbon inputs from crop residues over the 2006–2016 period and changes in soil organic C stock

The difference in the amount of the soil incorporated residues between the monoculture system and the rotation ones was mainly due to the amount of weeds aboveground residues that in the case of conventional monoculture accounted for about 50% of the total amount of residues (Figure 2). Estimated belowground residues (roots) followed the same trend, since they were calculated as a percentage of the aboveground biomass. Results indicate that in alternative monoculture system, 49.4% of residues was due to globe artichoke below and aboveground biomass, 39.5% to weeds, while 11.1% was due to the cover crop (bean). In the biannual rotation cauliflower residues account only for the 6.4% of the total amount or residues returned to soil at the end of the 10-year period.

Here Figure 2 The percent contribution of each system component in terms of residues (above and belowground) in conventional and alternative monoculture and biannual rotation cropping systems at the end of the 10-year period (2006-2016). Error bars indicate standard error of the means, n=10.

The cumulative C inputs in the ten years considered, increased with increasing of cropping system complexity, i.e. number of crops in the rotation, being 15% and 25% lower in conventional monoculture compared to alternative monoculture and biannual rotation respectively (Table 1). Focusing on the artichoke residues from above and belowground, the highest inputs were those of alternative monoculture, by about 33 and 55% higher than conventional monoculture and biannual rotation respectively. The inputs from weeds were high in all the treatments, even though, and as expected, slightly higher (numerically, but not statistically) in the conventional monoculture, for the long period in which the soil cover is left undisturbed, and lower in biannual rotation, with soil efficiently covered by the crops in the rotation. The soil C stock change is significantly higher in the conventional and alternative monoculture compared to the biannual rotation, roughly 114% higher ($p<0.01$). This might reflect the different composition and recalcitrance of residues incorporated to the soil. As a matter of fact, in conventional and alternative monoculture systems, the aboveground C inputs from artichoke residues, rich in lignin, are higher, namely 29 and 36% of the total (38 and 49% if we consider also the roots C input), compared to those of biannual rotation (in average 15%).

After incorporation, the decomposition and mineralization are largely biological processes, mainly due to the activity of the soil microorganisms (Kumar and Goh 2000; Zhu et al. 2015), and the decomposition of residues is normally negatively related to the rate of recalcitrant compounds present in their biomass, such as lignin, phenols, and tannins (Aber and Melillo 1982; Bertrand et al. 2006; Castellano et al. 2015). So, probably, artichoke residues with 22% in weight of lignin might undergo a slower degradation compared to the residues of the other crops, with less lignin content, namely around

6% and 11% in weight for cauliflower and bean respectively (Khedar et al., 2017, Puget and Drinkwater, 2001). This was also confirmed by the values of sequestration rates, namely 0.76 and 0.72 t C ha^{-1} yr^{-1} in conventional and alternative monoculture systems, whereas the average sequestration rate for the biannual rotation is slightly negative (-0. 2 t ha^{-1} yr^{-1}), despite a higher C input to the soil. The average negative C balance in the biannual rotation (-1.07 t C ha^{-1}) can be explained by two main factors: i) the cauliflower has a C/N ratio and a lignin content (12 and 6% respectively) lower than artichoke ,C/N 25 and lignin 22% Wt, and it was likely degraded faster; ii) the cover-crop (a leguminous species), rich in N (C/N 10), might caused a sort of *priming* effect, i.e. a stimulation of organic matter degradation when incorporated to the soil at the same time with cauliflower or artichoke residues (C/N 25) (Farina et al. 2018, Li et al., 2018). This accelerated decomposition phenomenon is also confirmed by the fact that, despite 12% higher cumulative C input to soil in the alternative monoculture respect to the conventional, the C sequestration rate is lower by 0.42 t C ha^{-1} probably for the above mentioned effects of the N added with plant residues of the leguminous cover-crop (Li et al., 2020). It should be also considered that in biannual rotation there are two additional tillage operations that might accelerate oxidation of organic matter by soil disturbance.

3.2. RothC simulations

Modification made to RothC regarding the DPM/RPM ratio of the artichoke residues, set to 1 (0.5 DPM and 0.5 to RPM) instead of the default for herbaceous crop 1.44 (0.59 DPM and 0.41 RPM), produced good simulation results (Figure 3). The modified DPM/RPM ratio for artichoke residues was adopted to consider their peculiar characteristics, with high content of lignin ranging from 10 to 24% of the dry matter (Fadda et al. 2018). For all the other C residues, namely weeds, cauliflower pea and bean, the default value of DPM/RPM was used. The RothC predictions were closely associated with the measured data. Indicators of performance were as follows: RMSE = 2 t ha^{-1}, $R^2 = 0.84$ ($p<0.05$) and EF = 0.78, demonstrating a good accuracy of simulations. To evaluate the model performance, we compared observed and predicted values, excluding the starting values used to initialize the model.

Here Figure 3 Scatter plot of observed versus predicted soil organic carbon content. The dotted line represents the 1:1 x:y relationship. Indicators of performance: RMSE = 2; R^2 = 0.84; EF = 0.78.

3.3. Change of C sequestration potential of the different systems

The RothC simulations mimicked accurately the C dynamics in the different artichoke cropping systems, as confirmed by the good score of the model performance indicators. Consequently, the model could be used confidently to predict the influence of climate change on the soil C sequestration potential. The three different climate scenarios allowed to explore a variety of combinations of temperature and rainfall patterns variations in future climate compared to the baseline situation. Twenty years predictions shown that all the systems, no matter of the climate scenarios considered, had a positive C balance, e.g. accumulated C in the soil. In the period considered, the SOC change (in t C ha^{-1} as difference between initial and final value) as average for the three climate scenarios, were: conventional monoculture +18% and +14% , alternative monoculture +24% and +22%, biannual rotation +10% and +8%, monoculture with residues removal + 4% and +1% for baseline and future climate scenarios, respectively (Table 3). Moreover, it is worth to mention that the two alternate systems of biannual rotation, one starting with cauliflower and the other with artichoke, showed very different SOC change at the end of the period, i.e. -5.2 and +1.36 t C ha^{-1}, wich is well mimicked also by simulations (Fig. 3).

Here Table 3 Modeled soil organic carbon change for each system averaged for the three climates scenarios

When we consider the soil C sequestration potential in future climate scenarios compared to baseline conditions, all the predictions point toward a possible reduction in this capacity. This result underlines the risk, reported also by other authors'modelling results, that changes of climate (e.g. rain and temperature increase) might negatively affect and even compromise the long-term fertility of intensively cultivated soils in Mediterranean regions (Francaviglia et al. 2012 for tilled vineyards, Munos-Rojas et al. 2017 for irrigated crops). Figure 4 graphically explains how the different cropping systems react to the projected climate changes, that in the considered area consists in increase of both rain and temperature. The graph is a three-dimensional one, where temperature change, rainfall change and soil organic potential sequestration of the systems, compared to baseline, are plotted to obtain an area. The greenish areas indicate a good resilience of the systems, where losses of the soil C sequestration capacity are at most 10%. In these conditions, any minor management adjustment (e.g modulation of irrigation, timing of residues incorporation, etc.) can be implemented according to the current climatic trend without substantial changes in the farming system. The yellowish areas indicate a situation of attention, with a medium risk of loss of C and where the loss of C storage capacity might be counterbalanced with changes in management practices devoted to C conservation (conservation tillage, organic fertilizer application, etc.), selected on the basis of the current climatic evolution. These types of adjustments might require a modification of the machinery, the selection of different sources of fertilisers (organic) and might involve a higher financial investment. The reddish areas indicate a high vulnerability of the system in terms of loss of C sequestration potential, with losses from 40% to 70% of the capacity to retain the C input into the soil. Systems that fall entirely within this area have little/no options for improvement and might be discarded to the advantage of more resilient systems.

Here Figure 4 3D surface plot of the potential soil C sequestration change (z axis) against temperature (T) (x axis) and rainfall (R) (y axis) changes, categorized by cropping system. All variables are expressed as rate of change from baseline to future climate values.

The alternative monoculture (Figure 4b) was the most resilient system and might be confidently adopted in the considered region, since it responded to all predicted climate changes with no significant reductions of C storage capacity. At the opposite, the no-residue system (Figure 4d) falls entirely within the red area: this means that, whatever the type of climate change, the conservation of soil C is at serious risk and therefore the loss of fertility is a realistic scenario (Cherubin et. al 2018). The other two systems (Figure 4a and 4c) fall partially in the green and in the yellow area, with notable differences. We show for the first time that in a conventional monoculture system, in case of temperature increase up to 0.6 °C together with limited rain increase (7%), the storage capacity of the C remains almost constant. On the other hand, with limited temperature increase but with maximum increase in rain (up to 16%), the system falls into the area of attention and will therefore require adjustments. The water availability and high temperature are considered the most important factors accelerating the breakdown of soil organic matter, since they concur to increase microbial activity, which induces SOM mineralization (Manzoni et al. 2012). This coupled effect of high temperature and soil moisture is duly considered in RothC, that predicted an increase of SOC decomposition in such conditions. On the other hand, RothC does not simulate crop development and possible positive effects of climate change on plant productivity, and hence on C input to soil that might compensate higher C decomposition. However, a recent review from Bisbis et al. (2018) questioned the positive effect of climate change on cauliflower productivity while effects on artichoke productivity are not known. Hence, the reduction of water supply proportional to rainfall increase appears a feasible adjustment, together with a proper planning of timing of irrigation as long as productivity is not negatively affected (Zornoza et al, 2016). According to our simulation, for both systems, increase of rainfall was the most important factor affecting negatively the C storage potential. For the first time, we have shown in a temporal perspective the importance of residues management in the Mediterranean artichoke-based systems to ensure the conservation of C stock in soils. Moreover, we have identified best management practices for the farmers as well as highlighted how the removal of the residues might lead to SOC depletion, with consequences on the overall soil quality, food security, supply and quality of water, biodiversity (Lal, 2015).

4. Conclusion

This study, to our best knowledge, for the first time predicts SOC stocks changes in globe artichoke-based cropping systems in Southern Europe using a biophysical model and a long-term experimental dataset. We have revealed, for the first time, that the most critical practice is represented by the removal of crop residues. This practice should be carefully considered when evaluating alternative options of the residues use, different from the incorporation to soil, i.e. biorefinery feedstock. Wether this option proves convenient for the farmer, C lost compensation strategies should be put in place to avoid OC depletion in soil. Among the other systems analysed, conventional and alternative monoculture showed a higher resilience to climate change, whereas the biannual rotation needs adjustments in the management, likely on irrigation regimes or organic fertilization.

The RothC model predictions under a climage change scenarios perspective allowed to identify the potential of different artichoke-based cropping systems to sequester SOC, as well as to discriminate such potential on the basis of the crops sequence. This kind of approach and the information obtained represents a useful tool for policy makers, both for the assessment of the past agricultural policies effects on SOC trends, and for future regional planning, because factors as climate change scenarios, land use and land management modifications can be considered at the same time. The methodology can be confidently applied to other regional estimations, also in other cropping systems, provided that relevant and long-term data series are available, despite the uncertainty due to the fact that RothC does not simulate plant growth. The other peculiarity of our study is that the database included actual cropping sequences, and hence reproduced with a high degree of accuracy the farm management and results can be already used to drive regional decisions.

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflicts of interest. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval

Not relevant for this research

Consent to participate

Not relevant for this research

Consent for publication (include appropriate statements)

Not relevant for this research

Availability of data and material (data transparency)

The data that support the findings of this study are available from the corresponding author upon reasonable request

Code availability (software application or custom code)

RothC is available and can be downloaded at Rothamsted Research (https://www.rothamsted.ac.uk/)

Authors' contributions (include appropriate statements)

Conceptualization, R.Fa. and L.L.; Methodology, R.Fa. and L.L.; Investigation, M.T.T.; Data Curation, P.A.D. and M.T.T.; Writing – Original Draft, P.A.D, R.Fa. and L.L.; Writing –Review & Editing, P.A.D., R.Fa., R.Fr., and L.L.

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Table 1 Mean cumulative carbon inputs from crop residues over the 2006–2016 period and changes in soil organic C stock

Cropping systems	Plant C input (t ha^{-1})									Soil organic C change (t ha^{-1})
	Artichoke		Cauliflower		Cover crop		Weeds		Total*	
	Aboveground	Roots[§§]	Aboveground	Roots[§§]	Aboveground	Roots[§§]	Aboveground	Roots[§§]		
Conventional monocolture	18.96 b	6.26 b	-	-	-	-	30.58	10.00	65.80 b	7.59 a
Alternative monoculture	26.86 a	10.74 a	-	-	6.11 b	2.38 b	21.24	8.28	75.61 ab	7.17 a
Biannual rotation	12.02 b	4.81 b	3.55	1.37	23.45 a	8.31 a	21.10	7.61	82.21 a	-1.95 b
Monocolture with residues removal [§]	4.74	6.26	-	-	-	-	30.58	10.00	51.58	1.02[§§§§]

*The total C input is the sum of C from artichoke residues + C from cauliflower residues + C from weeds + C.

Different letters indicate significant differences among cropping systems for each residue component ($p < 0.05$) according to Kruskal-Wallis test or Mann–Whitney U-tests. [§] Data estimated and used for modelling the hypothetical scenario. [§§] Calculated as percentage (30%) of the measured aboveground biomass [§§§] Average of the two alternate biannual rotations. [§§§§]Average of the three baseline climate scenarios

Table 2 Modelled soil organic carbon change in twenty years for each system averaged for the three climates

Cropping systems	Soil Organic C change* (t ha^{-1})		Soil C sequestration potential change under future climate (%)
	Baseline**	Future climate**	
Conventional monoculture	11.7	10.9	-0.07
Alternative monoculture	8.9	7.2	-0.19
Biannual rotation	5.7	4.0	-0.30
Monoculture with residues removal	2.0	0.6	-0.70

[*] Difference between final and initial SOC stock values averaged for the three climate scenarios

** Average of the three climate scenarios: METO-HC, DMI-HIRHAM5-ECHAM5 and ETHZ-CLM-HadCM3Q0.

Figure 1 The two phases of the biannual rotation system. The picture on the left shows the cauliflower phase, and the picture on the right the globe artichoke phase. In the biannual rotation management globe artichoke is grown in sequence to cauliflower. By contrast, in the traditional globe artichoke cultivation practice globe artichoke is grown in monoculture for many consecutive years.

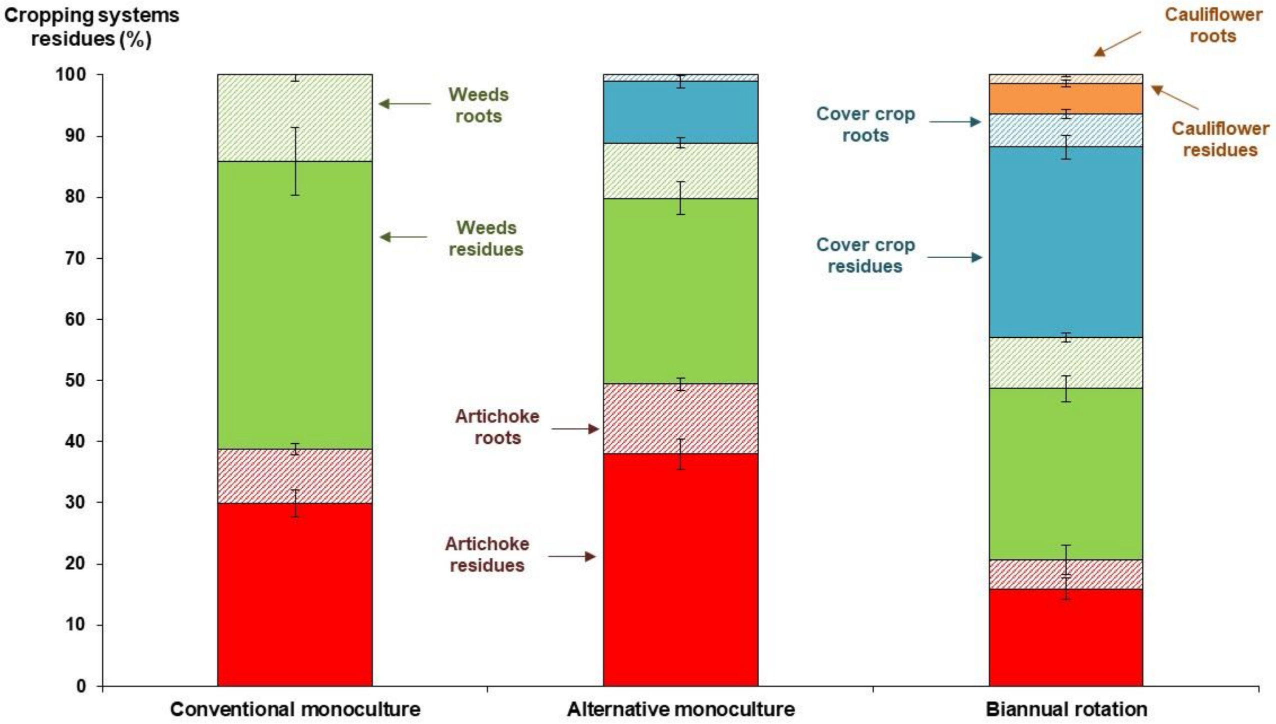

Figure 2 Figure 2 The percent contribution of each system component in terms of residues (above ground and belowground ones) towards conventional monoculture, alternative monoculture and biannual rotation cropping systems at the end of the 10-year period (2006-2016). Error bars indicate standard error of the mean, n=10.

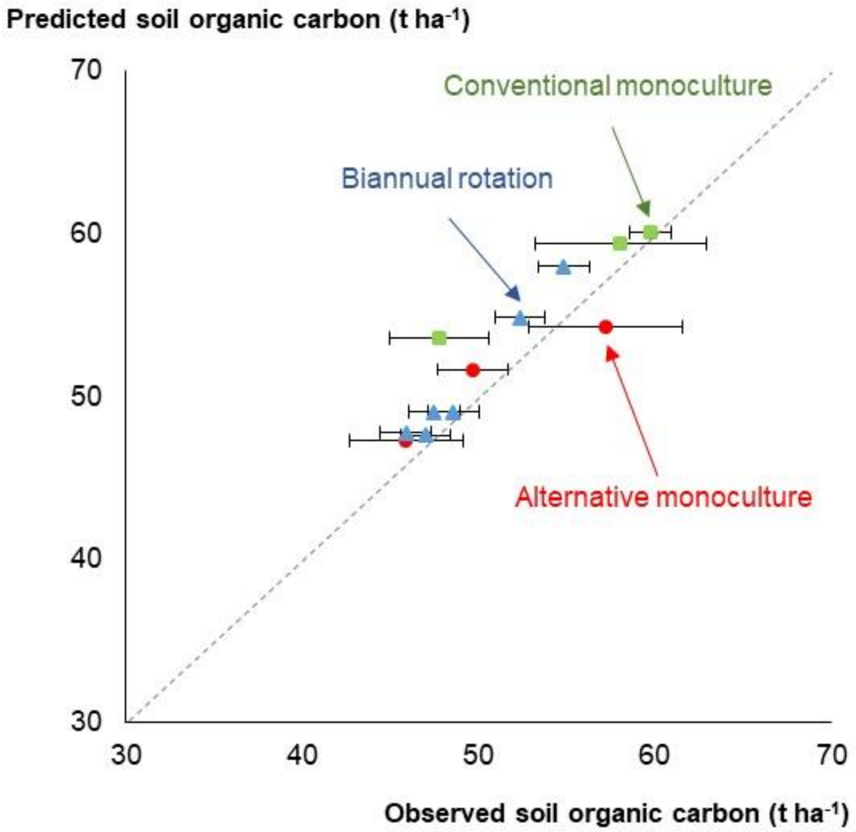

Figure 3 Scatter plot of observed versus predicted soil organic carbon content (N=12). The dotted line represents the 1:1 x:y relationship. Indicators of performance: RMSE= 2 t C ha^{-1}, R^2=0.84, EF=0.78

Figure 4

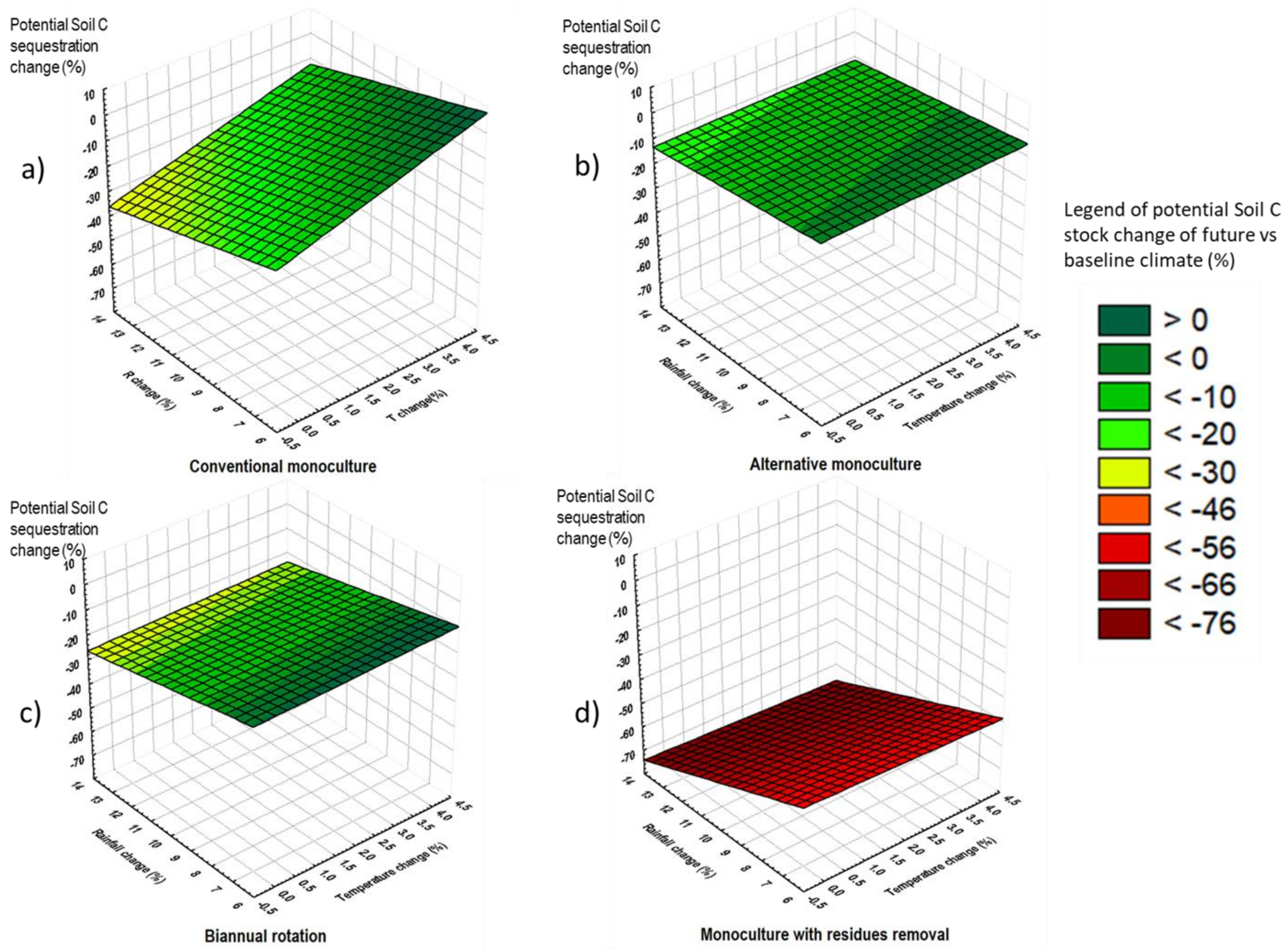
a)
Potential Soil C sequestration change (%)
10
0
-10
-20
-30
-40
-50
-60
-70
R change (%)
14
13
12
11
10
9
8
7
6
T change(%)
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Conventional monoculture
b)
Potential Soil C sequestration change (%)
Rainfall change (%)
Temperature change (%)
Alternative monoculture
c)
Potential Soil C sequestration change (%)
Rainfall change (%)
Temperature change (%)
Biannual rotation
d)
Potential Soil C sequestration change (%)
Rainfall change (%)
Temperature change (%)
Monoculture with residues removal
Legend of potential Soil C stock change of future vs baseline climate (%)
> 0
< 0
< -10
< -20
< -30
< -46
< -56
< -66
< -76

Figure 4 3D surface plot of the potential soil C sequestration change (z axis) against temperature (T) (x axis) and rainfall (R) (y axis) changes, categorized by cropping system. All variables are expressed as % rate of change from baseline to future climate values.