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

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1	Research Article
2	C-sequestration and resilience to future climate change of globe artichoke cropping systems greatly
3	depends on crop residues management
4	
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22	Abstract
23	Globe artichoke is one of the most intensively cultivated horticultural species in Mediterranean regions.
24	In this context, sustainable agronomic management is a requisite to increase the soil carbon content,
25	making the artichoke cultivation system more resilient to climate change. A ten-year experiment was
26	considered to forecast the influence on soil C dynamic of three globe artichoke managements:
27	monoculture with dry crop residues incorporation (conventional monoculture); monoculture with the
28	inclusion of a cover crop (alternative monoculture); rotation with cauliflower plus cover crop (biannual
29	rotation). During the 2006-2016 period, total soil organic carbon content and plant C inputs to soil were
30	measured. RothC model was used to predict the effect on the soil C stock and C sequestration potential
31	in 20 years of the three managements tested in the field, plus a hypothetical conventional scenario with
32	no residues' incorporation (no-residues). Plant C inputs increased according to the number of crops in
33	rotation in each system, resulting 25% lower in conventional monoculture with respect to biannual
34	rotation, whereas the C stock change was significantly higher (p<0.01) in conventional and alternative
35	monoculture (+ 7.57 and 7.14 t C ha ⁻¹) compared to biannual rotation (-1.03 t C ha ⁻¹). In the twenty
36	years predictions all the systems had a positive C balance. The soil organic carbon change (t C ha ⁻¹) for
37	the future climate was $+$ 7.2 for alternative monoculture, and $+$ 0.6 for monoculture with residues

38 removals. For the first time, in this study, we clearly shown in the long-term and in a climate change 39 perspective that an improper crop residues management might lead to a loss of soil fertility in 40 intensively cultivated horticultural soils under Mediterranean climate. The adoption of biannual rotation 41 with cauliflower needs to be evaluated carefully because it proved to be less efficient in terms of C

- 42 sequestration potential.
- 43

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

46

47 1. Introduction

48 In view of wellbeing, World Health Organization directions advocate an enhancement in vegetable 49 individual daily intake. Therefore, worldwide vegetable production is quickly increasing (FAO 2017). 50 Vegetable production is predominantly achieved through intensive horticultural systems. High rates of 51 chemical inputs (e.g. fertilizers, pesticides), repeated cultivation operations, and inadequate soil surface 52 cover are frequent issues threatening the preservation of soil quality (organic matter content and other 53 soil properties) in intensive horticultural systems (EIP-AGRI Focus Group 2015). Moreover, the high 54 application of chemicals also increases the probability that fertilizers and pesticides reach surface and 55 groundwater by runoff and leaching (Eurostat 2015). Soil health is somewhat impaired by intensive 56 agriculture, primarily for fertility depletion (e.g. soil organic matter). For some horticultural crops, only 57 a small amount of organic material is returned to the soil after harvest (Brennan and Acosta-Martinez 58 2017). Thus, horticultural cropping systems could have a serious negative effect on soil fertility and 59 ecosystem services delivery. Indeed, within the Mediterranean intensive horticultural systems, the 60 distribution of organic fertilizers based on humic and fulvic acid has become a common practice, in 61 relation to the need to improve cation exchange capacity of the soil and provide slowly available organic 62 nitrogen (Alvarenga et al. 2015; Urra et al. 2019). At present, agronomic studies have usually neglected 63 investigations on soil fertility in horticultural systems, and this may be regarded as an important research 64 shortcoming, which should be addressed with the aim to develop new knowledge to meet the demand 65 of sustainable food by a rising population (Norris et al. 2018). To improve soil fertility, different 66 alternative managements and agronomic techniques have been suggested, aiming also at reducing 67 external inputs and nutrients losses, e.g. stubble retention. Sustainably managed, agriculture can 68 minimize the impacts caused by intensification and foster the soil resilience in the long-term (Gomiero 69 et al. 2011). Over the past years, research has resulted in significant progress in developing 70 techniques/practices of crop production while reducing negative effects on soil quality and ecosystem 71 services delivery, i.e. adopting conservation agriculture with minimum tillage, and decreasing 72 exogenous fertilisers application by a sound use of crop rotations or pre-plant soil analysis (Knowler 73 and Bradshaw 2007). Nevertheless, these progresses were mainly addressed to open-field crops such as 74 cereals, mostly used for animal feeding (Cassidy et al. 2013) rather than to human consumption. To 75 enhance soil organic carbon (SOC) content and promote sustainability, an adjustment of management 76 is needed, including organic amendments both of animal and of plant origin, cover-crop or mulching, 77 and a lower number of cultural operations (EIP-AGRI Focus Group 2015). Globe artichoke (Cynara 78 cardunculus L. var. scolymus (L.) Fiori) is a horticultural species widely grown in Mediterranean 79 climate-type areas for its heads (Deligios et al. 2017). In Southern Italy, where the majority of the globe 80 artichoke cultivation is carried out, re-flowering genotypes (e.g. Spinoso sardo) are well adapted to 81 forcing techique (summer implantation by dormant offshoots, followed by frequent irrigations) and are 82 usually cultivated in monoculture (consecutively for seven or more years), with a large amount of 83 chemical fertilizers supply (e.g. 250 – 400 kg N ha⁻¹, Bianco and Calabrese 2009). The earliest head 84 productions of such genotypes (from October to February), because of their better quality and higher 85 commercial price, are destined for fresh consumption, while only the late ones (from late March to 86 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.

91 To promote alternative management of artichoke cropping systems, is of paramount importance to 92 enhance awareness of farmers and policy makers on advantages of an environmental sound crop 93 management. The adoption of more resilient cropping systems, aims to positively affect the soil C stock, 94 contributing significantly to adaptation and mitigation of climate change. However, providing advices 95 on best practices to reach the objective of increasing soil C content in soils is challenging, due to the 96 slow change of soil C in response to management (Mondini et al. 2012), often difficult to measure in 97 short-term field experiments. The combination of long-term experiments (> 6 years) and process-based 98 models has proved to be an effective approach to predict the soil carbon dynamics over long periods, 99 thus allowing for a long-term estimation of farming practices effects on SOC. Among the most used 100 models, RothC (Coleman and Jenkinson 1999) has proved to be well suited to simulate accurately the 101 soil C dynamics in several pedoclimatic situation and in Mediterranean cropping systems (Mondini et 102 al. 2012; Pardo et al. 2017; Farina et al. 2018). With specific regards to horticultural systems in the 103 Mediterranean region, a successful example of combining data from long-term experiments and 104 process-based model, is represented by the use of RothC with a dataset obtained from an Italian long-105 term horticulture experiment under organic management (Farina et al. 2018). We used a long-term field 106 experiment (Deligios et al. 2017) as a case-study representative of horticultural systems in the 107 Mediterranean area to predict the long term effect on soil C dynamic of alternative artichoke cropping 108 system management, namely: conventional monoculture with residue retainment in the field and 109 improved management of fertilization, alternative monoculture with bean as cover crop and biannual 110 rotation with cauliflower and pea as cover crop. Soil C content during the years and plant C inputs to 111 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 hier finance (D) A sing stall 2020). The mail improve feedback proton in terms of C corrected in a start of the still used practice of burning biomass.
- biorefinery (D'Avino et al. 2020). The resilience of each system, in terms of C sequestration potential,
- 116 to climate change was assessed.
- 117

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.

123

124 2. Material and Methods

125 2.1 Site and treatments description

126 The long-term field experiment is ongoing since 2006 at the experimental farm 'Mauro Deidda' few 127 kilometers apart from Sassari, in Sardinia (Southern Italy: 40°46'N, 8°29'E). Following the Köppen-128 Geiger climate classification (Beck et al. 2018), the experimental site has a hot- summer Mediterranean 129 climate, with warm winters, hot and dry summers, and with the highest precipitation in autumn and 130 winter. During the studied period (2006–2016), the mean annual temperature, precipitation and 131 potential evapotranspiration were 16.6 °C, 529 and 776 mm respectively. The soil is Lithic Xerochrept 132 (USDA 1999) developed on a limestone bedrock with 49.0% sand, 24.3% silt and 19.6% clay (sandy 133 clay loam). In 2006, at the start of the experiment the topsoil (0–20 cm) soil organic C content ranged 134 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 135 Deligios et al. (2017). Globe artichoke, 'Spinoso sardo' varietal type, was grown according to three 136 different crop managements: a conventional monoculture, and two sustainable systems (alternative 137 monoculture and biannual rotation). The experimental field (in total 4080 m^2) was organized according 138 to a randomized block design with three treatments and three replications. Blocks and plots were 139 separated by approximately 3 m.

140 To mimic the traditional forcing technique (Ledda et al. 2013), every year since 2006, after plowing at

141 25 cm depth and harrowing at 10 cm, at beginning of July, the 10-cm-long semi-dormant offshoots of

142 Spinoso sardo artichoke were planted. The distance between plants within a row was 70 cm, achieving

143 a density of around 9500 plants ha⁻¹. Drip irrigation of approximately 300 mm was applied to the entire

144 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).
- 147 The conventional monoculture was carried out according to the ordinary practice of local farmers,148 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
- 153 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
- 160 artichoke growing cycle.
- 161 In the biannual rotation system, a two-year rotation artichoke-cauliflower (Brassica oleracea L. var. 162 *botrytis*; cv Nautilus) (Clause Italia SpA, Italy) was set-up on alternate plots; thus, all phases of the crop 163 sequence were present in the field every year. Moreover, each year in February, in inter-row spaces, a 164 pea cover crop (Pisum sativum L.; cv Attika) (Limagrain Verneuil Holding, France) was systematically 165 sown after an interow rotary harrowing pass (10-cm depth). At the end of the harvest period, both for 166 cauliflower and globe artichoke, all fresh residues, including those of the cover-crop, were chopped and 167 incorporated into the soil by rotary-harrowing at 20-cm depth. Two months after incorporation, the beds 168 in all plots were plowed at 25-cm depth and harrowed at 10 cm for the next cauliflower or artichoke 169 production cycle. In the two sustainable systems, plant nutrients demand was satisfied by the plant fresh 170 residues incorporated to soil, since the aim was to design a cropping system without external chemical 171 fertilisers input. Morever, the alternative monoculture and biannual rotation systems were conducted 172 without synthetic pesticide use.
- 173

174 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-m² 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.

- 186 Plant samples were fractionated into two parts. One part was dried at 55 °C to constant weight and
- 187 stored for nutrient analysis; another part was dried at 80°C for 24 hours (up to weight stabilization) for
- 188 the determination of the dry matter content. All the organic biomass utilized as C input was analyzed

189 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
- 191 biomass was estimated as 30% of the aboveground biomass for all the crops.
- 192

193 2.3 Modeling

194 The RothC model (Coleman and Jenkinson 1999) simulates SOC dynamics and has been tested in a 195 large range of pedoclimatic conditions and cropping system management. The model requires relatively 196 easily available inputs and produces reliable and accurate simulations (Francaviglia et al. 2012; Farina 197 et al. 2018; Robertson and Nash 2013). Soil C is split into five pools: four active compartments, 198 decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and 199 humified organic matter (HUM), each decomposing by a first order kinetics and specific decomposition 200 rate (years⁻¹), and one inert organic matter pool (IOM). All C inputs, from plants or external organic 201 fertilizers, are split between DPM and RPM, with a variable ratio depending on the type of material. 202 Both DPM and RPM decompose to form CO₂ (lost from the system), BIO and HUM, depending from 203 soil clay (Coleman and Jenkinson 1999).

204

205 2.3.1 Running RothC

206 Running RothC requires the following:

- 207 (a) Climatic data: Monthly rainfall (mm), potential evaporation (mm) and mean air temperature
 208 (°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).

213 For RothC running, the potential evapotranspiration (ET) was calculated from measured weather data 214 using the Thornthwaite equation. The irrigation amount was calculated by the difference between 215 rainfall and ET and slightly corrected in order to keep available water at 80% during the irrigation period 216 (from July to November) (350 mm as average). The bulk density, used to transform mg of C per kg of 217 soil in t C ha⁻¹, was the average of the measurements in all plots at the beginning of the experiment. 218 RothC was initialized using the SOC content measured at the beginning of the experiment using the 219 default partitioning among the SOC pools. The model was run iteratively to equilibrium (10.000 years) 220 in order to generate the input required to match the initial stock of SOC, and then calibrated with the 221 conventional treatment. The aboveground C inputs of the artichoke and weeds were measured, whilst 222 belowground were estimated according to Raccuia and Melilli (2010) for artichoke and Farina et al.

- 223 (2018) for cover crops, cauliflower and weeds considering a root:shoot ratio of 0.3. The total C input 224 was divided into monthly fractions according to the crop phenological stage following Raccuia and 225 Melilli (2010), ranging from a fraction of 0.05 at crop establishment to a 0.35 one at maximum biomass 226 development.
- 227 The model was calibrated using the conventional monoculture treatment and included the modification 228 of artichoke residues partitioning coefficient of the pools DPM and RPM, by adjusting the relative rate 229 to fit the measured C changes in the soil (Heitkamp et al. 2012). All the other treatments were used to 230 validate the model, with 18 pair of data (measured and modeled), not considering the data used for 231

initialization and calibration, according to the different land management.

232

233 2.3.2 Predictions of C sequestration potential in the medium term (20 years) for the different systems 234 We run the model for the different cropping systems to assess the medium-term potential to accumulate 235 soil C, using averaged field data for C inputs, irrigation and soil cover and climate projection (baseline 236 and future climate scenarios). Twenty years of simulated weather data were obtained by AGRI4Cast 237 Resource Portal (https://agri4cast.jrc.ec.europa.eu/DataPortal/), consisting in daily weather data for 238 Europe (on a 25×25 km grid) by three General Circulation Models: (1) METO-HC (METO); (2) DMI-239 HIRHAM5-ECHAM5 (ECHAM); and (3) ETHZ-CLM-HadCM3Q0 (ETHZ) of the MARS-240 AGRI4CAST as Daily weather data for crop modelling over Europe derived from climate change 241 scenarios (available at https://agri4cast.jrc.ec.europa.eu/DataPortal/, last accessed the 28th December 242 2020). The model was run with the baseline (1990-2010) and future (2011-2030) climate projections, 243 obtained by each of the three General Circulation Models. Projected baseline weather data were 244 comparable with those measured in the long-term. The temperature and rainfall changes in future 245 climate scenarios compared with current situation were as follow: METO no change of temperature and 246 + 13% of rainfall; ECHAM +0.35°C and +7% rainfall; ETHZ +0.6°C and +13% rainfall.

247 In addition to the simulations of the cropping systems tested in the field, we run also a hypothetical 248 reference system of conventional artichoke with residues removed from the field (monoculture with-249 residues removals), representing a realistic situation where artichoke residues are burnt or removed as 250 biomass for biorefinery utilization. The C inputs used to run this scenario were the same of the 251 conventional monoculture for weeds and artichoke roots, wheareas we assumed that 75% of the 252 artichoke aboveground biomass is removed, whatever the use, based on data reported by D'Avino et al. 253 (2020) in a similar system. Inputs for the biannual rotation are reported as average of the two fields. 254 Irrigation was not modified under future climate, to simulate a condition very common in Italy where 255 farmers have normally a fixed amount of water (350 mm in our case) distributed by the Water Use 256 Associations (Consorzi di bonifica). The resilience to future climate change of each cropping system is 257 expressed as change in C sequestration potential i.e. % difference between SOC change in 20 years 258 between baseline and future climates.

259

260 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
- 263 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–
- 265 Whitney U-test (instead of the t-test). All statistical tests were performed using SAS software (SAS v
- **266** 9.2 1999).

267 C sequestration potential of the different systems in the field and after 20 years of simulation were

268 indicated as C stock change and obtained as:

269 *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 followingindicators:

274 i) RMSE (root mean square error),

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

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;

279 ii) coefficient of determination (R²) of the linear regression estimates versus measurements
280 (association), ranging from 0 (absence of fit of the regression line) to 1 (perfect fit of the regression
281 line): the closer the values are to 1 the better the model performance;

282
$$R^{2} = \frac{\sum_{i=1}^{n} (P_{i} - O_{i}) \cdot (O_{i} - \overline{O})}{\sqrt{\sum_{i=1}^{n} (P_{i} - \overline{P})^{2} \cdot \sum_{i=1}^{n} (O_{i} - \overline{O})^{2}}}$$

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

285
$$EF = 1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$$

- 286
- 287 where, P_i and O_i are the ith simulated and observed values respectively, \overline{P} and \overline{O} the average simulated 288 and observed values respectively, and n the total number of observations.
- 289

290 **3. Results and discussion**

291 3.1 Crop residues, C inputs and soil C stock change in the field experiment

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

293

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

296

297 The difference in the amount of the soil incorporated residues between the monoculture system and the 298 rotation ones was mainly due to the amount of weeds aboveground residues that in the case of 299 conventional monoculture accounted for about 50% of the total amount of residues (Figure 2). 300 Estimated belowground residues (roots) followed the same trend, since they were calculated as a 301 percentage of the aboveground biomass. Results indicate that in alternative monoculture system, 49.4% 302 of residues was due to globe artichoke below and aboveground biomass, 39.5% to weeds, while 11.1% 303 was due to the cover crop (bean). In the biannual rotation cauliflower residues account only for the 6.4% 304 of the total amount or residues returned to soil at the end of the 10-year period.

305

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.

310

311 The cumulative C inputs in the ten years considered, increased with increasing of cropping system 312 complexity, i.e. number of crops in the rotation, being 15% and 25% lower in conventional monoculture 313 compared to alternative monoculture and biannual rotation respectively (Table 1). Focusing on the 314 artichoke residues from above and belowground, the highest inputs were those of alternative 315 monoculture, by about 33 and 55% higher than conventional monoculture and biannual rotation 316 respectively. The inputs from weeds were high in all the treatments, even though, and as expected, 317 slightly higher (numerically, but not statistically) in the conventional monoculture, for the long period 318 in which the soil cover is left undisturbed, and lower in biannual rotation, with soil efficiently covered 319 by the crops in the rotation. The soil C stock change is significantly higher in the conventional and 320 alternative monoculture compared to the biannual rotation, roughly 114% higher (p<0.01). This might 321 reflect the different composition and recalcitrance of residues incorporated to the soil. As a matter of 322 fact, in conventional and alternative monoculture systems, the aboveground C inputs from artichoke 323 residues, rich in lignin, are higher, namely 29 and 36% of the total (38 and 49% if we consider also the 324 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

- 331 6% and 11% in weight for cauliflower and bean respectively (Khedar et al., 2017, Puget and Drinkwater, 332 2001). This was also confirmed by the values of sequestration rates, namely 0.76 and 0.72 t C ha⁻¹ yr⁻¹ 333 in conventional and alternative monoculture systems, whereas the average sequestration rate for the 334 biannual rotation is slightly negative $(-0.2 \text{ t } \text{ha}^{-1} \text{ yr}^{-1})$, despite a higher C input to the soil. The average 335 negative C balance in the biannual rotation $(-1.07 \text{ t C } \text{ha}^{-1})$ can be explained by two main factors: i) the 336 cauliflower has a C/N ratio and a lignin content (12 and 6% respectively) lower than artichoke C/N 25 337 and lignin 22% Wt, and it was likely degraded faster; ii) the cover-crop (a leguminous species), rich in 338 N (C/N 10), might caused a sort of *priming* effect, i.e. a stimulation of organic matter degradation when 339 incorporated to the soil at the same time with cauliflower or artichoke residues (C/N 25) (Farina et al. 340 2018, Li et al., 2018). This accelerated decomposition phenomenon is also confirmed by the fact that, 341 despite 12% higher cumulative C input to soil in the alternative monoculture respect to the conventional, 342 the C sequestration rate is lower by 0.42 t C ha⁻¹ probably for the above mentioned effects of the N 343 added with plant residues of the leguminous cover-crop (Li et al., 2020). It should be also considered 344 that in biannual rotation there are two additional tillage operations that might accelerate oxidation of 345 organic matter by soil disturbance.
- 346

347 3.2. RothC simulations

348 Modification made to RothC regarding the DPM/RPM ratio of the artichoke residues, set to 1 (0.5 DPM 349 and 0.5 to RPM) instead of the default for herbaceous crop 1.44 (0.59 DPM and 0.41 RPM), produced 350 good simulation results (Figure 3). The modified DPM/RPM ratio for artichoke residues was adopted 351 to consider their peculiar characteristics, with high content of lignin ranging from 10 to 24% of the dry 352 matter (Fadda et al. 2018). For all the other C residues, namely weeds, cauliflower pea and bean, the 353 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, 354 355 demonstrating a good accuracy of simulations. To evaluate the model performance, we compared 356 observed and predicted values, excluding the starting values used to initialize the model.

357

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; R² = 0.84; EF = 0.78.

361

362 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 368 predictions shown that all the systems, no matter of the climate scenarios considered, had a positive C 369 balance, e.g. accumulated C in the soil. In the period considered, the SOC change (in t C ha⁻¹ as 370 difference between initial and final value) as average for the three climate scenarios, were: conventional 371 monoculture +18% and +14%, alternative monoculture +24% and +22%, biannual rotation +10% and 372 +8%, monoculture with residues removal +4% and +1% for baseline and future climate scenarios, 373 respectively (Table 3). Moreover, it is worth to mention that the two alternate systems of biannual 374 rotation, one starting with cauliflower and the other with artichoke, showed very different SOC change 375 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. 376 3).

377

378 Here Table 3 Modeled soil organic carbon change for each system averaged for the three climates379 scenarios

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381 When we consider the soil C sequestration potential in future climate scenarios compared to baseline 382 conditions, all the predictions point toward a possible reduction in this capacity. This result underlines 383 the risk, reported also by other authors' modelling results, that changes of climate (e.g. rain and 384 temperature increase) might negatively affect and even compromise the long-term fertility of 385 intensively cultivated soils in Mediterranean regions (Francaviglia et al. 2012 for tilled vineyards, 386 Munos-Rojas et al. 2017 for irrigated crops). Figure 4 graphically explains how the different cropping 387 systems react to the projected climate changes, that in the considered area consists in increase of both 388 rain and temperature. The graph is a three-dimensional one, where temperature change, rainfall change 389 and soil organic potential sequestration of the systems, compared to baseline, are plotted to obtain an 390 area. The greenish areas indicate a good resilience of the systems, where losses of the soil C 391 sequestration capacity are at most 10%. In these conditions, any minor management adjustment (e.g. 392 modulation of irrigation, timing of residues incorporation, etc.) can be implemented according to the 393 current climatic trend without substantial changes in the farming system. The yellowish areas indicate 394 a situation of attention, with a medium risk of loss of C and where the loss of C storage capacity might 395 be counterbalanced with changes in management practices devoted to C conservation (conservation 396 tillage, organic fertilizer application, etc.), selected on the basis of the current climatic evolution. These 397 types of adjustments might require a modification of the machinery, the selection of different sources 398 of fertilisers (organic) and might involve a higher financial investment. The reddish areas indicate a 399 high vulnerability of the system in terms of loss of C sequestration potential, with losses from 40% to 400 70% of the capacity to retain the C input into the soil. Systems that fall entirely within this area have 401 little/no options for improvement and might be discarded to the advantage of more resilient systems. 402

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.

406

407 The alternative monoculture (Figure 4b) was the most resilient system and might be confidently adopted 408 in the considered region, since it responded to all predicted climate changes with no significant 409 reductions of C storage capacity. At the opposite, the no-residue system (Figure 4d) falls entirely within 410 the red area: this means that, whatever the type of climate change, the conservation of soil C is at serious 411 risk and therefore the loss of fertility is a realistic scenario (Cherubin et. al 2018). The other two systems 412 (Figure 4a and 4c) fall partially in the green and in the yellow area, with notable differences. We show 413 for the first time that in a conventional monoculture system, in case of temperature increase up to 0.6 414 °C together with limited rain increase (7%), the storage capacity of the C remains almost constant. On 415 the other hand, with limited temperature increase but with maximum increase in rain (up to 16%), the 416 system falls into the area of attention and will therefore require adjustments. The water availability and 417 high temperature are considered the most important factors accelerating the breakdown of soil organic 418 matter, since they concur to increase microbial activity, which induces SOM mineralization (Manzoni 419 et al. 2012). This coupled effect of high temperature and soil moisture is duly considered in RothC, that 420 predicted an increase of SOC decomposition in such conditions. On the other hand, RothC does not 421 simulate crop development and possible positive effects of climate change on plant productivity, and 422 hence on C input to soil that might compensate higher C decomposition. However, a recent review from 423 Bisbis et al. (2018) questioned the positive effect of climate change on cauliflower productivity while 424 effects on artichoke productivity are not known. Hence, the reduction of water supply proportional to 425 rainfall increase appears a feasible adjustment, together with a proper planning of timing of irrigation 426 as long as productivity is not negatively affected (Zornoza et al, 2016). According to our simulation, 427 for both systems, increase of rainfall was the most important factor affecting negatively the C storage 428 potential. For the first time, we have shown in a temporal perspective the importance of residues 429 management in the Mediterranean artichoke-based systems to ensure the conservation of C stock in 430 soils. Moreover, we have identified best management practices for the farmers as well as highlighted 431 how the removal of the residues might lead to SOC depletion, with consequences on the overall soil 432 quality, food security, supply and quality of water, biodiversity (Lal, 2015).

433 4. Conclusion

This study, to our best knowledge, for the first time predicts SOC stocks changes in globe artichokebased 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
- 446 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 useand land management modifications can be considered at the same time. The methodology can be
- 449 confidently applied to other regional estimations, also in other cropping systems, provided that relevant
- 450 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
- 453 be already used to drive regional decisions.
- 454

455 Declarations

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- 458 **Conflicts of interest/Competing interests**
- 459 The authors declare that they have no conflicts of interest. The authors have no affiliation with any
- 460 organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.
- 461 The authors declare that they have no known competing financial interests or personal relationships that
- 462 could have appeared to influence the work reported in this paper.
- 463 Ethics approval
- 464 Not relevant for this research
- 465 Consent to participate
- 466 Not relevant for this research
- 467 **Consent for publication (include appropriate statements)**
- 468 Not relevant for this research
- 469 Availability of data and material (data transparency)

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

- 471 reasonable request
- 472 Code availability (software application or custom code)
- 473 RothC is available and can be downloaded at Rothamsted Research (<u>https://www.rothamsted.ac.uk/</u>)
- 474 Authors' contributions (include appropriate statements)

- 475 Conceptualization, R.Fa. and L.L.; Methodology, R.Fa. and L.L.; Investigation, M.T.T.; Data Curation,
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- 478

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- 591

Table 1 Mean cumulative carbon inputs from crop residues over the 2006–2016 period and changes in soil organic C sto	and changes in soil organic C stock
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	Plant C input (t ha ⁻¹)						Soil organic C			
Canadian systems	Artichoke		Cauliflower		Cover crop		Weeds		Toto1*	change (t ha ⁻¹)
Cropping systems	Aboveground	Roots ^{§§}	Aboveground	Roots§§	Aboveground	Roots§§	Aboveground	Roots ^{§§}	- I otal*	(,
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			

climates						
Cropping systems	Soil Org	ganic C change* (t ha ⁻¹)	Soil C sequestration potential			
	Baseline**	Future climate**	- change under future chinate (%)			
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			

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

*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.



Predicted soil organic carbon (t ha-1)

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 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.