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Title: Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis

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Abstract: Mediterranean woody crops, such as olive and almond farming, and vineyards are usually cultivated in soils low in organic matter, with limited water availability and frequently on medium to steep slopes. Therefore, when conventionally cultivated, soils of these cropping systems are net sources of CO2 (throughout soil erosion and organic carbon mineralization). A promising option to sequester carbon (C) in these cropping systems is the implementation of recommended management practices (RMPs), which include plant cover in the inter-row area, minimum or no tillage and off- and on-farm organic matter amendments. However, the effects of RMPs on soil organic carbon (SOC) stocks in these cropping systems are widely overlooked, despite the critical importance of estimating their contribution on CO2 emissions for policy decisions in the agriculture sector in Mediterranean regions. We therefore conducted a meta-analysis to derive a C response ratio, soil C sequestration rate and soil C sequestration efficiency under RMPs, compared to conventional management of olive and almond orchards, and vineyards (144 data sets from 51 references). RMPs included organic amendments (OA), plant cover (CC) and a combination of the two (CMP). The highest soil C sequestration rate (5.3 t C ha-1 yr-1) was observed following the application OA in olive orchards (especially after olive mill pomace application), whereas CC management achieved the lowest C sequestration rates (1.1, 0.78 and 2.0 t C ha-1 yr-1, for olive orchards, vineyards and almond orchards, respectively). Efficiency of soil C sequestration was greater than 100% after OA and CMP managements, indicating that: i) some of the organic C inputs were unaccounted for, and ii) a positive feedback effect of the application of these amendments on SOC retention (e.g. reduction of soil erosion) and on protective mechanisms of the SOC which reduce CO2 emissions. Soil C sequestration rate tended to be highest during the first years after the change of the management and progressively decreased. Studies performed in Mediterranean sub-climates of low annual precipitation had lower values of soil C sequestration rate, likely due to a lower biomass production of the crop and other plant cover. Soil C sequestration rates in olive farming were much higher than that of vineyards, mainly due to the application of higher annual doses of organic amendments. The relatively high sequestration rate combined with the relative large spatial extent of these cropping system areas suggests that the adoption of RMPs is a sustainable and efficient measure to mitigate climate change.

Dear Sundar Ananthakrishnan, Journal Manager

We appreciate the time and constructive comments that the editor and reviewers dedicated to our manuscript again.

Annexed to this cover letter, we have written the response to the comments of the reviewers and a detailed description of the changes carried out after revision. Briefly, we have assumed most of the reviewers concerns and comments and we have made clearer in the text some issues raised by the reviewer. In this line, most of the comments of the Editor have been also assumed.

In addition, we have reinforce the importance of our results compared to other similar meta-analysis and for that purpose we made some changes in the manuscript which are described in the annexed document.

We hope that these changes improved the understanding and potential of our results, and the overall quality of the manuscript and thus it could be now considered for its publication in Agriculture, Ecosystems and Environment. In case of further queries, we are happy to clarify them.

Looking forward to your response,

Yours truly,

J.L Vicente-Vicente & Roberto García-Ruiz, corresponding authors, on behalf of the authors.

Responses to the reviewer comments and concerns

Editor:

“Highlights: max length should 85 characters”

Highlights have been rewritten as follows:

- Effects of RMPs on SOC in woody crops were assessed using literature data
- Average SOC sequestration rate for all RMPs was 3.8 t C ha^{-1} yr^{-1}.
- C sequestration rates in olive orchard ranged 1.1 (CC) to 5.3 (OA) t C ha^{-1} yr^{-1}.
- C sequestration rate in vineyards was 0.78 t C ha^{-1} yr^{-1} in CC management.
- C sequestration rates were highest during the first years of the RMPs

“Conclusions: Still too much of a summary; please reduce to some key concluding remarks”

According to the advice, conclusions have been rewritten, thus finally obtaining a shorter paragraph and remarking those results being more relevant.

“Table 1: Explain all abbreviations in a footnote”

We did not include a footnote explaining the abbreviations, since they are explained in the “Description” and “Observations” sections of Table 1. We think that including a footnote explaining the abbreviations would be a bit redundant, since Table 1 is specifically shown to describe the different managements, inputs and tillage methods.

“Figures: Please use larger fonts”

According to this advice, we have increased the font of the all the figures.

Reviewer #2

Specific comments:

“Eq. 4. I recommend to replace k with j. K could result in misunderstanding (it could be mixed up with a rate constant)”

We totally agree with this comment of the reviewer. Therefore, it has been changed.

L. 371-372 of the new version. Please present in a new table the mean temperature and rainfall for each sub-climate regions used in the study.

We acknowledge the comment of the reviewer. We decided to not to include a table with values of temperature and precipitations due to the high complexity of the Köppen-Geiger climate classification. As it is shown in the figures below (Kottek *et al*., 2006), each climate is defined by three letters. Second letter corresponds to precipitations and the third one to the air temperature conditions. We considered that include all this information in a table would not be so much helpful to the paper and, for that reason we decided to include only the full name of each climate (e.g. Csa (Warm temperate, dry summer, hot summer)) and referring the table to this paper of Kottek *et al*., 2006.

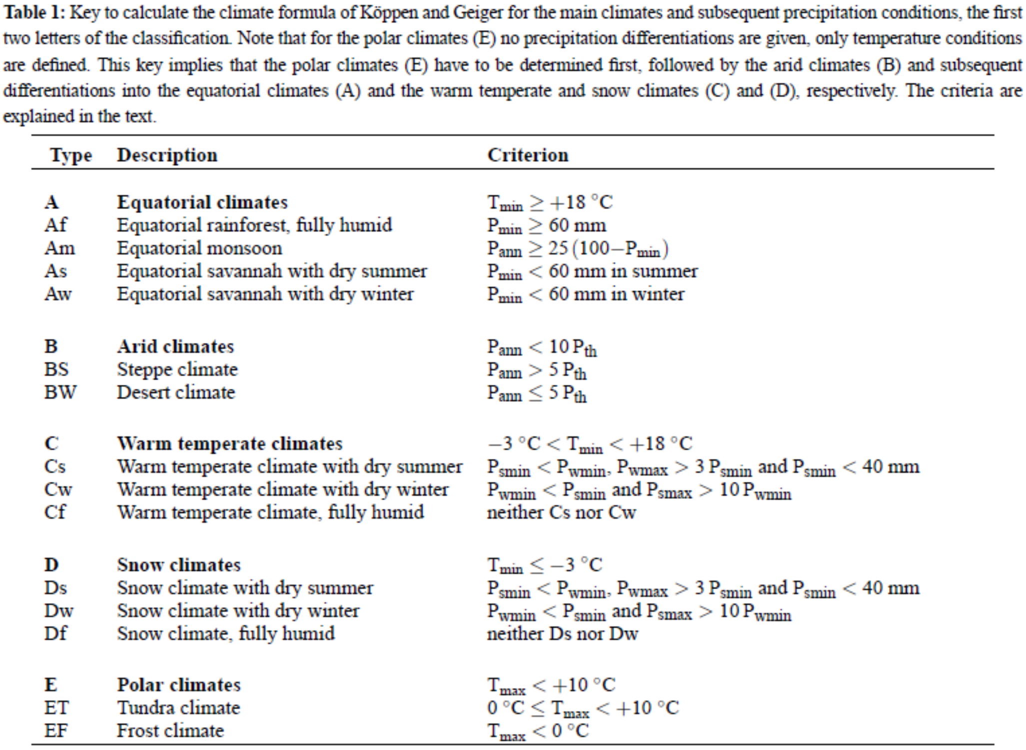

Table 1: Key to calculate the climate formula of Köppen and Geiger for the main climates and subsequent precipitation conditions, the first two letters of the classification. Note that for the polar climates (E) no precipitation differentiations are given, only temperature conditions are defined. This key implies that the polar climates (E) have to be determined first, followed by the arid climates (B) and subsequent differentiations into the equatorial climates (A) and the warm temperate and snow climates (C) and (D), respectively. The criteria are explained in the text.

Type	Description	Criterion
A	**Equatorial climates**	$T_{min} \geq +18\,°C$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\,(100-P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$P_{ann} < 10\,P_{th}$
BS	Steppe climate	$P_{ann} > 5\,P_{th}$
BW	Desert climate	$P_{ann} \leq 5\,P_{th}$
C	**Warm temperate climates**	$-3\,°C < T_{min} < +18\,°C$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Cf	Warm temperate climate, fully humid	neither Cs nor Cw
D	**Snow climates**	$T_{min} \leq -3\,°C$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\,P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\,P_{wmin}$
Df	Snow climate, fully humid	neither Ds nor Dw
E	**Polar climates**	$T_{max} < +10\,°C$
ET	Tundra climate	$0\,°C \leq T_{max} < +10\,°C$
EF	Frost climate	$T_{max} < 0\,°C$

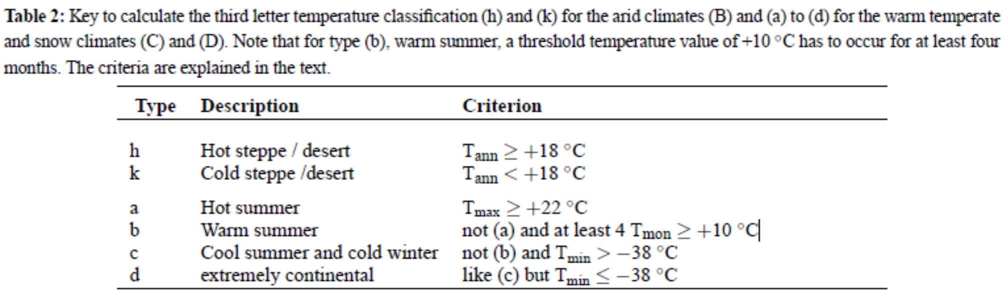

Table 2: Key to calculate the third letter temperature classification (h) and (k) for the arid climates (B) and (a) to (d) for the warm temperate and snow climates (C) and (D). Note that for type (b), warm summer, a threshold temperature value of +10 °C has to occur for at least four months. The criteria are explained in the text.

Type	Description	Criterion
h	Hot steppe / desert	$T_{ann} \geq +18$ °C
k	Cold steppe /desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	not (b) and $T_{min} > -38$ °C
d	extremely continental	like (c) but $T_{min} \leq -38$ °C

Therefore, we still consider that it would be better to include only the reference and the full name of the climate, so that the reader can read the whole climatic information in Kottek *et al*., 2006.

“L. 388-393 of the first version. SOC sequestration rate from the RMP cannot be compared to the conventional treatment (not data available to calculate SOC seq rate in conventional treatment). If RMP sequestration rate is greater than 1 implies that RMP is sequestering C compared to its initial value. But it does not mean that it is sequestering greater SOC than the conventional treatment since the SOC sequestration rate of the conventional treatment is unknown. It is a serious error to consider that, in all the studies used, C levels in the conventional treatment are in steady-state conditions”

We really appreciate this reviewer’s comment, since we agree with that comment. For that reason in L. 273-276 (first revision) we include the following paragraph: “When data of SOC at the beginning of the experiment were not available, values of SOC stocks in the CONV treatment were selected, assuming similar initial C levels in RPM and CONV plots, since the plots used for the comparisons in the different studies had similar pedoclimatic conditions”.

Effectively, this assumption has two consequences. First, that the plot under the conventional tillage must have similar pedoclimatic conditions than those of the RPM. For that reason, we took into account that in each paper was well described in the M&M section that the conventional plot was near the plot applying the RPM and, thus, having similar soil conditions. Secondly, it is true that we assumed that the plots under conventional tillage were in equilibrium. We consider that this assumption is usually right in woody crops, since the conventional tillage is the main and most widespread management in Mediterranean woody crops, at least since the appearance of the herbicides (due to its relatively low cost and easiness to be applied). Otherwise, woody crop farmers do not usually change the crop due to some economic and social reasons (e.g. the high cost of removing olives, the culture of olive oil and wine). As a consequence, it is very common to find woody crops which have been under conventional tillage for decades. Therefore, for these reasons we think that the majority of the woody crop soils under a conventional tillage were in equilibrium.

“One main concern of the first version of the manuscript was the novelty of the results. Authors needed to show that the paper really implies an advance to the understanding of the topic. In the response to reviewer comments, authors defended the novelty of the paper and the importance of the study. I do not agree with one of the points highlighted by the authors. In particular they justified the study with the next sentence "…there are no published studies comparing the ability of perennial fruit tree plantations to fix atmospheric C into the soil under RPMs." This statement is contradictory in a meta-analysis presenting a large number of studies dealing with the impacts of RMP on soil C sequestration in fruit tree systems.

We acknowledge this comment and, thus, the opportunity to make it clear. Effectively, we should have written “there are no published large studies or meta-analysis comparing the ability of perennial fruit tree plantations to fix atmospheric C into the soil under RPMs in Mediterranean conditions”. Thus, this sentence has been rewritten in the Introduction section (L. 145-147).

Furthermore, according to the 1st new insights of the study listed in the response to reviewer comments, I understand that the number of studies used in this new meta-analysis is larger than the number of fruit tree studies used in the Aguilera et al. (2013) paper. Please, in the Material and Methods section present and compare the total number of tree orchard studies used in both meta-analysis.

I strongly recommend the authors present new Page and Line numbers when they have made a change to the manuscript in response to review comments. It saves time to the Reviewers.”

We acknowledge, these comments. We agree with the reviewer that we should have been included the comparisons used in Aguilera et al. (2013) meta-analysis. In order to solve this problem we have included the following sentence “These 123 comparisons represent a strong increase of available data compared to those found by Aguilera et al. (2013), who assessed the C sequestration rate in Mediterranean woody crops by using 10 comparisons” (see 2.4 section of M&M “Statistical analysis” L.322 – 324).

Highlights

- Effects of RMPs on SOC in woody crops were assessed using literature data
- Average SOC sequestration rate for all RMPs was 3.8 t C ha^{-1} yr^{-1}.
- C sequestration rates in olive orchard ranged 1.1 (CC) to 5.3 (OA) t C ha^{-1} yr^{-1}.
- C sequestration rate in vineyards was 0.78 t C ha^{-1} yr^{-1} in CC management.
- C sequestration rates were highest during the first years of the RMPs

Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis

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Abstract

Mediterranean woody crops, such as olive and almond farming, and vineyards are usually cultivated in soils low in organic matter, with limited water availability and frequently on medium to steep slopes. Therefore, when conventionally cultivated, soils of these cropping systems are net sources of CO_2 (throughout soil erosion and organic carbon mineralization). A promising option to sequester carbon (C) in these cropping systems is the implementation of recommended management practices (RMPs), which include plant cover in the inter-row area, minimum or no tillage and off- and on-farm organic matter amendments. However, the effects of RMPs on soil organic carbon (SOC) stocks in these cropping systems are widely overlooked, despite the critical importance of estimating their contribution on CO_2 emissions for policy decisions in the agriculture sector in Mediterranean regions. We therefore conducted a meta-analysis to derive a C response ratio, soil C sequestration rate and soil C sequestration efficiency under RMPs, compared to conventional management of olive and almond orchards, and vineyards (144 data sets from 51 references). RMPs included organic amendments (OA), plant cover (CC) and a combination of the two (CMP). The highest soil C sequestration rate (5.3 t C ha^{-1} yr^{-1}) was observed following the application OA in olive orchards (especially after olive mill pomace application), whereas CC management achieved the lowest C sequestration rates (1.1, 0.78 and 2.0 t C ha^{-1} yr^{-1}, for olive orchards, vineyards and almond orchards, respectively). Efficiency of soil C sequestration was greater than 100% after OA and CMP managements, indicating that: i) some of the organic C inputs were unaccounted for, and ii) a positive feedback effect of the application of these amendments on SOC retention (e.g. reduction of soil erosion) and on protective mechanisms of the SOC which reduce CO_2 emissions. Soil C sequestration rate tended to be highest during the first years after the change of the management and progressively decreased. Studies performed in Mediterranean sub-climates of low annual precipitation had lower values of soil C sequestration rate, likely due to a lower biomass production of the crop and other plant cover. Soil C sequestration rates in olive farming were much higher than that of vineyards, mainly due to the application of higher annual doses of organic amendments. The relatively high sequestration rate combined with the relative large spatial extent of these cropping system areas suggests that the adoption of RMPs is a sustainable and efficient measure to mitigate climate change.

Keywords

Soil organic carbon, carbon sequestration, Mediterranean woody crops, recommended management practices

1. Introduction

In terrestrial ecosystems, soil organic carbon (SOC) is by far the largest pool of organic carbon and globally contains over 1550 Pg C, followed by the soil inorganic carbon (SIC) pool (750-950 Pg C) and terrestrial vegetation (600 Pg C) (Schimel, 1995). Therefore, the soil C pool (SOC plus SIC) is about four times larger than the terrestrial vegetation and three times larger than the atmospheric carbon (C) pools. The net annual increase in atmospheric CO_2-C is estimated to be about 4.3 Pg yr^{-1} (Ciais et al., 2013). Consequently, even a small annual percent change in the amount of C stored or released from SOC stocks could easily affect the net change in atmospheric-CO_2 (Smith, 2012).

Forests and grasslands contain high stocks of C and are considered as net sink of C, while croplands often act as net sources of CO_2 due to soil disturbance which enhance soil organic carbon decomposition and to field management involving direct (e.g., diesel fuel for machinery) or indirect (e.g., chemicals) emissions of fossil fuels (Ceschia et al., 2010). Indeed, agriculture and land use change are together responsible for 21-24% of global anthropogenic greenhouse gas emissions (Smith et al., 2014; Tubiello et al., 2015).

Finding low-cost methods to sequester C in agricultural systems is emerging as a major international policy goal in the context of increasing concerns about global climate change. Among the methods that may reduce agricultural CO_2-derived greenhouse gas emissions, there is the adoption of recommended management practices (RMPs), which involves an accumulation of organic C in the soil without compromising crop production. In agricultural systems, the gain or loss of C over time due to cultivation (e.g. net ecosystem C balance) depends on the amount of C entering (for example through organic amendments or cover crops residues) and on that leaving the system (e.g. harvest of products, soil and plant respiration). In terms of SOC balance, RMPs reduce the oxidation of SOC and increase organic C inputs (Six et al., 2004). A reduction of the SOC oxidation can be achieved by changing the tillage type from conventional tillage (CT) to reduced tillage (RT) or no-tillage (NT). The increase in organic C input on farm can be achieved by the use of a cover crop (CC) in the rotations, or allowing the growth of wild vegetation in the inter-row of perennial orchard-type crops. Off-farm organic inputs can also be used for this purpose, such as manure, compost, or agro-industrial and urban wastes. Lal (2004) estimated a potential C sequestration for croplands by adopting RPMs in the range of

0.4 – 0.8 Pg C yr^{-1}, with similar, but at the lower end, estimates from IPCC (Smith et al., 2008; 2014)

Fruit orchards, such as olive groves and almond, and vineyards, are usually cultivated where soil fertility is relatively low and water availability limited, and therefore they are relatively well adapted to Mediterranean climates. These perennial crops represent about 16% of the agricultural land in the Mediterranean area (FAO data, 1998) and are of a great economic importance (Olesen and Bindi, 2002).

In comparison with annual crops (Smaje, 2015), fruit orchards have some structural features allowing them to potentially sequester significant quantities of atmospheric C. Their long life cycle allows them to accumulate C in permanent organs such as trunk, branches, and roots and in the soil (e.g. rhizodeposition). In addition, the massive and deep-rooted systems in these perennial woody crops allow direct transfer of SOC into the subsoil, making it less prone to mineralization. However, some conventional management of these cropping systems might lead to significant losses of SOC. Usually, conventional management involves bare soil in the inter-canopy area of the orchards, through regular tillage and/or pre- and post-emergence herbicides, leading to SOC losses not only because of the higher mineralization rates but also because of higher erosion rates. For example, Gomez et al. (2004) measured annual rates of soil losses in a conventional olive grove (4.0 t ha^{-1} yr^{-1}) which is 3.3 times higher than in a comparable plot where the soil was covered with spontaneous resident vegetation (1.2 t ha^{-1} yr^{-1}). Since the Mediterranean climate is characterized by relatively frequent, extreme, short-lasting rainfall events, erosion represents a problem, especially in high slope areas that can be solved – or minimized – by implementing RMPs. The relevance of SOC changes to the net greenhouse gases balance of cropping systems can be very large, particularly in the specific case of

Mediterranean woody crops. In a life-cycle assessment study under Mediterranean conditions in Spain, Aguilera et al. (2015) found that soil C sequestration in organic olive orchards was equivalent to all other emissions combined, resulting in C-neutral crop production.

Soil C accumulation in these fruit orchards can be achieved relatively easily, both economically and technically, through the adoption of RPMs which include: i) reduced or zero soil tillage, which preserves soil organic matter from mineralization; ii) the frequent presence of herbaceous vegetation in the alleys, which can contribute to the build-up of soil organic matter, and iii) the inputs of external (e.g. manure) and internal (e.g. pruning debris) sources of organic matter. In addition, some fruit orchard crops have relatively low yields with a tendency to partition less C to the fruits than high-yielding ones and, therefore, some of the C fixed by photosynthesis enters the detritus cycle. In addition, improving soil resilience through increased SOC may positively impact the whole fruit tree industry. Increased knowledge of atmosphere-soil C fluxes mechanisms may facilitate interventions capable of enhancing C capture (Marland et al., 2004).

In spite of the strategic role of orchards and vineyards in Mediterranean regions (Olesen and Bindi, 2002), the role of RPMs on C fixation potential has only partially been explored. In recent years, the C budget of fruit tree plantations has received increasing attention with studies conducted in olive (Nardino et al., 2013; Sofo et al., 2005), palm (Navarro et al., 2008), apple (Zanotelli et al., 2015), peach (Sofo et al., 2005), and pear (Zhang et al., 2013). However, unlike other systems such as croplands (Ceschia et al., 2010; Smith, 2004), grasslands (Derner and Schuman, 2007; O’Mara, 2012) and forests (Barr et al., 2002; Vogt, 1991), there are no published large studies or meta-analysis comparing the ability of perennial fruit tree plantations to fix atmospheric C into the soil under RPMs in Mediterranean conditions.

Some recent meta-analyses have provided insight on the role of specific or grouped management practices on SOC. For instance, Poeplau and Don (2015) assessed the influence of cover crops on SOC stocks, Tuomisto et al. (2012) analysed the impacts of the organic farming in Europe on SOC content, nutrient losses, energy requirements or land use, Tian et al. (2015) assessed the influence on SOC changes of the addition of different fertilizers and crop residues in paddy soils in China, and Zhao et al. (2015) identified the management practices that lead to an increase in the SOC content in China. However, these studies do not distinguish between herbaceous and woody crops, and usually only herbaceous crops are considered. Aguilera et al. (2013) performed the first meta-analysis of SOC sequestration in Mediterranean crops, with 174 data sets from 79 different publications. The results of this study showed a high response of SOC to management changes under Mediterranean conditions. However, this work did not specifically focus on woody crops, and most of the studies were focussed on annual herbaceous crops, so the effects of specific RMPs designed only for woody crops were not specifically evaluated. In addition, the C sequestration efficiency and the effects of sub-climates, and the duration of implementation of the RMPs on SOC sequestration, were not assessed in this study. The influence of specific RMPs for woody crops on SOC sequestration and C sequestration efficiency is essential for estimating the contribution of the woody crops subjected to different management practices on CO_2 emissions, which is of critical importance for policy decisions in the agriculture sector in Mediterranean regions.

The aim of this study was to evaluate the influence of specific RMPs on SOC content of three common Mediterranean woody crops (olive orchards, vineyards and almond orchards), through a meta-analysis. We compared SOC in: i) Conventionally managed (used as control) without vegetation cover in the inter-row of the orchards and without any organic amendments; ii) Farms with a vegetation cover in the inter-row, iii) Farms with organic amendment inputs, and iv) Combined management practices.

2. Materials and methods

2.1 *Literature review and data selection*

A literature search was conducted for articles reporting comparisons between RMPs and conventional management in three typical Mediterranean woody crops: olive and almond orchards and vineyards. All the studies were carried out in areas under a Mediterranean climate type. Laboratory studies were excluded and only studies under field conditions were selected. We did not distinguish between irrigation and no irrigation, since irrigation in Mediterranean woody crops is usually done under the tree canopy, near the trunk and soil samples are usually taken in the inter-row area. When more than one study included data from the same experiment, the longest study was selected. If the duration of the study was the same in both cases, the study with most information was included in the analysis.

The studies included in the analysis were those cited in Scopus until January of 2016. Two fields where used for the search in the title, abstract or keywords of the article. The first field was the crop type, using the following words: “olive” or “vineyard” or “almond” or “*Olea europea*” or “*Vitis vinifera*” or “*Prunus dulcis*”. For the second field, the search terms “soil organic carbon” and “soil organic matter” were used. Thereafter, we only included in the meta-analysis those studies conducted under Mediterranean climate. We obtained 213 results, resulting in 60 potential articles. This search was completed with other studies cited in Aguilera et al. (2013).

2.2 *Definition of categories*

The types of C input were those summarised in Table 1, namely: (i) None: no external organic C input was applied. The growth of a cover consisting of natural plant cover was prevented by frequent tillage and/or by pre-emergence herbicides. (ii) CC: a cover crop (seeded plant cover) or a cover of spontaneous resident vegetation (unseeded cover) in the inter-row area. Sheep or goat excretion resulting from grazing of these plant covers was included in this category since it is not an external organic input and the input of organic C by this route is typically very low. (iii) CR: crop residues, such pruning residues or olive leaves which were left on the top soil. (iv) OA: an external organic amendment was applied frequently. This external amendment typically consisted of farmyard manure, composted or un-composted olive mill pomace or sewage sludge. A wide range of doses and biochemical properties of these external organic amendments was found.

For the tillage types we used the following categories (Table 1). (i) T: frequent tillage. Tillage consisted of 3 or more annual passes. Very often this is combined with the use of herbicides. This tillage method was common in the conventional (CONV) management. (ii) RT: reduced tillage. This tillage method was common in the studies where wild resident vegetation covered the inter-row area of the farm. Reduced tillage was usually done during the spring to control the vegetation. (iii) NTH: no tillage, and unwanted plants were controlled using pre-emergence herbicides. As a consequence, the soil is permanently bare. As in the case of the T, NTH is common in the CONV management. (iv) NTM: no tillage and wild resident plants are eliminated by mowing, or using post-emergence herbicides in the spring. (v) NTG: no tillage where unwanted plants were controlled by animal grazing.

The comparisons were classified by management according to Table 1. The management is a result of the tillage and the type of organic C input. Conventional management (CONV) was used as a control group in the majority of the comparisons. CONV management typically includes the use of mineral fertilizers under the T tillage category. The rest of the management practices belong to the RMPs group. Some of these were the same as those proposed by Aguilera et al. (2013). (i) CC: a cover crop was implemented in the inter-row area or the orchard or vineyard. In most cases the soils were covered by a community of natural resident vegetation which was allowed to grow, typically between early autumn to middle spring. This plant community was controlled by mowing, grazing, or by applying post-emergence herbicides during the spring. Aboveground plant residues were left on the soil surface or incorporated by tillage. (ii) OA: organic amendments (manure, compost, agroindustry by-products or other residual organic inputs) were applied. Crop residues, such as pruning debris were included in this category. The growth of unwanted plants was prevented by tillage or application of pre-emergence herbicides. (iii) CMP: combined management practices. This is the most environmentally-friendly management category. It includes the existence of plant cover (cover crop or resident vegetation cover) or an inert cover (crop residues), combined with an organic amendment. In some cases, plants were controlled by grazing.

The influence of four variables (Table 2) on the calculated effect sizes was assessed: management, woody crop species, time and climate. Management is a variable which includes: OA, CC, CC + OA (CMP) and none. In this analysis, three typical Mediterranean woody crop species were distinguished: olive orchards (*Olea europaea*), vineyards (*Vitis vinifera*), and almond orchards (*Prunus dulcis*). According to the duration of the study, the studies were classified into 3 categories: (i)

Short-term: less than 6 years, (ii) Medium-term: 6 – 10 years, (iii) Long-term: more than 10 years. Finally, 6 different sub-climates of the Mediterranean climate according to Köppen-Geiger classification were also distinguished (Kottek et al., 2006): Csa, Csb, Cfa, Cfb, BWh and BSk (see Table 2 for the description of the different Mediterranean sub-climates).

Unfortunately, the influence of the different Mediterranean sub-climates and the duration of the study were only assessed for the CC management, since for OA and CMP managements, the high variability of the C inputs and the low number of studies with a duration longer than 5 years made the analysis impossible.

2.3 *Data management*

An effect is a statistical measure that portrays the degree to which a given event is present in a sample (Cohen, 1969). An effect size is a standard measure which can be calculated from any number of statistical outputs. We assessed 3 effect sizes (Table 3): (i) SOC response ratio, (ii) C sequestration rate, and (iii) efficiency of C sequestration. Data measured in most studies were SOC concentrations (g C kg^{-1} soil, or mg C g^{-1} soil). When data of the studies were presented only in a figure and not in numeric format, data were extracted from figures using WebPlotDigitizer software (http://arohatgi.info/WebPlotDigitizer) after figure digitalization. When soil organic matter concentration was determined instead of SOC, SOC was calculated using the Mann (1986) relationship (SOC = 0.58 x SOM).

SOC response ratio was calculated applying the eq. 1:

$$\text{SOC response ratio (RR)} = \frac{SOC_{RMP}}{\text{SOC}_{\text{Control}}} \qquad (1)$$

where $\mathrm{SOC_{RMP}}$ and $\mathrm{SOC_{Control}}$ are the SOC concentrations (g C kg^{-1} soil) measured in the RMP management and in the control (CONV management) farms, respectively. Nevertheless, in order to normalize the sampling distribution, the natural logarithm of the RR was used (Hedges et al., 1999). Thus, the final equation was (eq.2):

$$\ln(RR) = \ln SOC_{RMP} - \ln SOC_{Control} \tag{2}$$

We assumed a significant response ratio under a specific management when values were significantly different from 1 ($\mathrm{e.g.\,SOC_{RMP}} > \mathrm{SOC_{Control}}$).

To calculate soil C sequestration rate (t C ha^{-1} yr^{-1}) the change in the SOC stock (t C ha^{-1}) was calculated according to eq. 3.

$$\text{Soil C sequestration rate} = \frac{C_t - C_{t\prime}}{t} \tag{3}$$

where C_t and $C_{t\prime}$ represent SOC stocks (t C ha^{-1}) at the end and the beginning of the experiment, respectively, while *t* stands for the duration of the experiment (years). We assumed significant positive C sequestration rate under a specific RMP management relative to CONV management when values were significantly different from zero.

When data of SOC at the beginning of the experiment were not available, values of SOC stocks in the CONV treatment were selected, assuming similar initial C levels in RPM and CONV plots, since the plots used for the comparisons in the different studies had similar pedoclimatic conditions. Some studies provided the data of SOC stocks. However, most studies did not show values of SOC stocks, so these were calculated following the equation (eq. 4):

$$\text{SOC Stock (t C } ha^{-1}) = \sum_{\mathrm{i=1}}^{\mathrm{j}} \frac{\mathrm{d_i \rho_i SOC_i}}{10} \tag{4}$$

where d_i, ρ_i and SOC_i are soil depth (metres), bulk density (t m^{-3}) and SOC concentration (g C kg^{-1} soil) for the different soil layers (from i to j soil layers), respectively. The SOC stock was the sum of the stocks for the k soil layers considered in each study. Since bulk density was not provided in many of the studies, values were estimated using the algorithm used by Aguilera et al. (2013), which was modified from Howard et al. (1995) but re-parametrized with data from Mediterranean soils (eq. 5):

$$\rho\ (\mathrm{t}\ m^{-3}) = 1.84 - 0.443 \log 10\ (\mathrm{SOC}\ (\mathrm{g\ C}\ kg^{-1} soil)) \tag{5}$$

In the case of the studies providing enough information on the amount and characteristics of the organic inputs (both internal and external) – especially for OA and CR inputs – we also calculated the efficiency (E) of soil C sequestration following the equation (eq. 6):

$$\mathrm{E} = \frac{\text{C sequestration rate}}{\text{Annual organic C input}} \times 100 \tag{6}$$

2.4 *Statistical analysis*

We used a meta-analysis technique to assess the influence of RMPs on SOC using data from CONV management as the reference. A meta-analysis is a quantitative research synthesis which analyses the results of a set of analyses (Glass, 1976). The meta-analysis used a methodology similar to that used previously by Aguilera et al. (2013). For the meta-analysis, only independent studies were considered. We considered as independent studies those differing in management, duration, pedoclimatic or geomorphology conditions. For the non-independent studies, an average was calculated in order to avoid redundancy of the data and, thus, to transform them into independent values.

A “random-effects model” was used to carry out the meta-analysis. This type of model allows data from a wide range of scenarios to be compared (Borenstein et al., 2009), and assumes that the dispersion of data for a given category is not only due to a sampling error, but also due to other sources of variation which might have an effect on the mean effect size and the dispersion of the data (Borenstein et al., 2009). The dispersion of the data was relatively high in some cases and, therefore, it was difficult to detect significant differences.

The database contains 144 comparisons from 51 references. Nevertheless, not all the references contained all of the necessary data to calculate the effect sizes. Thus, we found 135 comparisons of SOC concentrations, and in 123 the C sequestration rate was shown or was calculated. These 123 comparisons represent a strong increase of available data compared to those found by Aguilera et al. (2013), who assessed the C sequestration rate in Mediterranean woody crops by using 10 comparisons. Finally, in 49 comparisons, the efficiency of C sequestration was calculated. In the case of the efficiency calculations, the majority of the data belonged to the studies which applied an organic amendment or crop residues. The studies which included cover crops did not usually show the amount of the inputs of organic C through plant residues.

Results of effect sizes were weighted in order to give more importance to larger studies (those with higher number of samples). Meta-analysis studies usually use the inverse of the variance of each study to weight the results. However, it was not possible in our case because this information was not provided for most of the studies. Thus, studies were weighted by sample size according to the methodology proposed by Adams (1997) (eq. 7):

$$w'_i = \frac{N_i^{RMP} N_i^{CONV}}{N_i^{RMP} + N_i^{CONV}} \tag{7}$$

Where *w'* refers to the specific weight of the comparison, and the N^{RMP} and N^{CONV} represent sample sizes in the recommended (RMP) and control (CONV) treatments, respectively.

As a result of a bootstrapping procedure (999 iterations) using MetaWin software (Rosenberg et al., 2000), 95% confidence intervals (CIs) were generated for each weighted mean effect size. Resampling techniques can be important for determining the significance of meta-analytic metrics since data often have small sample sizes and may violate some basic distributional assumptions. Bootstrapping chooses *n* studies from a simple size of *n* and then calculates the statistic, and this process is repeated many times to generate a distribution of possible values. The lowest and highest 2.5% values are chosen to represent the lower and upper 95% bootstrap confidence limits.

3. Results and discussion

3.1 *General information*

A total of 51 studies were selected resulting in 144 independent comparisons between the RMP and the CONV managements, i.e. about 3 comparisons per study. The number of studies performed in Spain was the highest (33 studies), followed by Italy (7), Greece (2), France (2), Portugal (2), South Africa (2), Syria (1), Turkey (1) and the United States (California) (1). According to the crop type, olive orchards were the most common woody crop (31 studies) studied, followed by vineyards (16) and almond orchards (5). One study included olive orchards and vineyards.

The number of studies devoted to olive groves and vineyards was somewhat related to their areas. Indeed, olive orchards in Spain and Italy cover 2.5 and 1.14 million hectares, respectively. However, this was not the case for almond orchards, at least in

Spain and California, where there are about 700,000 ha and 331,000 ha planted, respectively. Therefore, the number of studies on almond orchards was underrepresented in comparison to those on olives and vineyards. This fact might be due to the lower economic importance of the almond products in comparison to olive oil and wine. Most of the studies were published during the last 10 years, peaking during 2012 and 2013 (figure 1).

The duration of the study in 64 out of 144 comparisons was lower than 6 years, whereas in 37 and 22 of them it was between 6 - 10 years and more than 10 years, respectively (some studies do not show data about the duration of the management). The relatively short time frame (typically lower than 4 years) of most of research programs at National and EU levels is likely the responsible for the relatively high proportion of studies which evaluate changes in SOC over the short term. This contrasts with the fact that changes in SOC typically occur at different rates after a change in management practices. Indeed, Poeplau and Don (2015) found that highest rates of SOC accumulation occur during the first few years, and usually decline afterwards until near zero changes when the steady state is reached. Thus the data on SOC accumulation provided in most of the articles of this study might be overestimated if interpolated over time. Clearly, long-term experiments would be highly valuable to fully understand soil C dynamics over long periods.

Only studies under a Mediterranean-type climate were selected. However, mean annual rainfall and temperature vary according to the geomorphological properties and other geographical features of the experimental sites. The great majority of the comparisons (95) were undertaken under warm temperate conditions with relatively hot and dry summers (Csa type climate), followed by BWh (14), BSk (11), Cfb (9), Csb (12) and Cfa (3). This was especially true for olive orchards. Nevertheless, studies on vineyards were also done in Csb, Cfb and BWh climate types, whereas for almonds, the studies were also performed under a BSk type climate.

3.2 *Influence of management on the effect sizes of soil C sequestration*

Response ratios of the three tested managements (CMP, CC and OA) ranged 1.35 - 1.45 and averaged 1.40, and were significantly different from 1.0. There were not large differences in the response ratios of the three managements (figure 2a). The mean lowest value (1.35) was observed in farms under CC, whereas intermediate values were obtained for the CMP (1.40) management, and the highest (1.45) for the farms that received organic amendments.

The similarity in the SOC response ratios among RMP managements contrasts with the relatively large differences in C sequestration rates. This might be related to the differences between bulk densities and soil depths considered among the studies, since the same response ratio does not mean same C sequestration rate when different depths and bulk densities are considered. Thus, the C sequestration rate would be more appropriate than response ratio when assessing the influence of management practices on the changes of SOC in studies which include data from different depths.

Figure 2b shows that annual C sequestration rate averaged 4.07 t C ha^{-1} yr^{-1} under OA management. This figure was about 1.5 times higher than the rate found for CMP (2.62 t C ha^{-1} yr^{-1}) and four fold that under CC (1.03 t C ha^{-1} yr^{-1}), although these mean values were obtained with wide confidence intervals. For the whole set of studies and the three management types, minimum, mean and maximum annual C sequestration rates were -0.5, 3.8 and 6.6 t C ha^{-1} yr^{-1}. The fact that an accumulation of SOC was detected in the majority of the studies means that inputs of organic C and/or the slow-down of SOC losses under RMPs management compensate for SOC losses by organic matter decomposition and soil erosion. The average annual C sequestration rate for the whole set of studies was higher than that described for annual crops. For instance, Aguilera et al., 2013, in their meta-analysis involving Mediterranean crops, found a change of only about +8% in SOC content in the cereal rotations in the organic treatments compared to conventional management. The majority of cropping systems are dominated by annual plants that rely on cycles of tillage and planting of seed to ensure sufficient productivity. By comparison, fruit tree orchards, such as olives, almond and vineyards are capable of surviving many seasons requiring less soil disturbance. Perennial cropping systems have been recently proposed as systems that could protect soil C well, and since perennial plants often rely on more extensive root systems to ensure longevity, they likely produce more belowground biomass (Cox et al., 2006).

The highest SOC sequestration rate in the fruit tree orchards and vineyards was achieved for organic amendment management. For the whole set of studies under the OA management, the mean rate of organic C added was about 1.6 times higher than in CMP management, so the relatively high annual rate of C sequestration under the OA management compared to the other management practices is not surprising. The lower annual rate of organic carbon inputs in CMP compared to OA treated farms was likely due to the fact that farmer think that there is no need to add a high annual dose of organic matter when a cover crop is implemented in the inter-row area.

The fact that organic amendment additions represent direct inputs of organic C into the soil systems, and that these materials are often in forms that are much more recalcitrant than plant fresh residues should, in the absence of additional constraints, translate into moderate to high C sequestration rates. It is important to note that applications of manure are often assumed to increase C sequestration in soils at farm scale, but not at higher spatial scale (e.g. application of manure in one farm means an inefficient transport of organic C from other ecosystems to this farm), but manure is not likely to yield a net sink for C in soils (Smith, 2012), as would be required by the Kyoto protocol and also the Paris Agreement. Therefore, an ideal option would be apply organic C sources coming from the by-products of olive oil, wine and almond industries, thus avoiding CO_2 emissions from long-distance transportation, and from waste management.

The mean annual C sequestration rate reported here for CC was lower than the average of 1.59 t C ha^{-1} yr^{-1} found by the meta-analysis carried out by González-Sánchez et al. (2012) from 13 olive farms of Andalusia with CC. By using plant cover in the inter-row of tree orchards, an annual input of C is ensured, and this is true independently of the plant cover control technique. For instance, Castro et al. (2008) found a 3-year average annual aboveground biomass input of between 2.6 – 4.0 t ha^{-1} in an olive farm in Jaén (East Andalusia) with unseeded plant cover. The relatively high C sequestration rate under the CC treatment might be due not only to the annual C input of the plant residues, but also due to a decrease in C losses from soil erosion. In this line, Gomez et al. (2004) found a reduction in soil losses (and thus of organic matter and C) of about 70 % in an olive farm after the implementation of unseeded plant cover.

In addition, the diversity of unseeded plant cover might have an important impact on soil C accrual by improving the ability of soil microbial communities to rapidly process plant residues and protect them into aggregates. The presence of many different annual plants in unseeded plant cover also introduces a greater diversity of C compounds into the soil, some of which may be more resistant to decomposition

(Tiemann et al., 2015). While previous theories stated that microbial processing of residues in soils eventually produced similar C pools and compounds, a recent laboratory experiment found that the initial chemistry of the plant residues and the microbial community had a strong influence on which C compounds are present in the soil (Wickings et al., 2012). The presence of a diversity of plants, then, might ensure that a diversity of C compounds is present in the soil, improving soil C sequestration potential. Thus, strategies which increase productivity of non-commercial biomass without compromising the quantity and quality of the economic products, such as the inter-row seeded or unseeded cover in fruit tree orchards, is desirable to increase the amount of biomass C returned to the soils, which can affect the size, turnover, and vertical distribution of SOC (Franzluebbers et al., 1994). If suited to the climate and the technical and economic viability of the farming operation, then such cropping systems provide an opportunity to produce more biomass C than in a monoculture system, and to thus increase SOC sequestration. Lal et al. (1997) reviewed the literature on this topic and concluded that the potential for sequestering C by the application of cover crops residues was about 0.1 – 0.3 t C ha^{-1}, values much lower than those reported in our study for fruit tree orchards. However, the degree of intensification (more tillage events) of soils in these crops systems reviewed by these authors was much higher, likely with more SOC losses.

C sequestration efficiency is commonly expressed by the relationship between annual C input and SOC accumulation rate, which is an indicator of soil C sequestration ability (McLauchlan, 2006). Therefore, information about C sequestration efficiency is useful for seeking management strategies of enhancing the SOC stocks and soil fertility. On average, C sequestration efficiency was over 100% for OA (241%) and CMP (164%), whereas it was as low as 34% under CC management (Figure 2c).

Variability in soil C sequestration efficiency was ample, especially for CC and CMP managements, and no significant differences between groups were found. C sequestration efficiency is regulated by climate, the quantity and quality of added organic materials, soil organic C and inherent soil properties (Freibauer et al., 2004). These factors might explain the great variability observed in this study, which compiles many studies with wide pedoclimatic variability, and diverse quantities and qualities of the organic C amendments. High soil C efficiency in fruit tree orchards systems was expected, as these are usually cultivated on soils with low organic matter, and a negative linear relationship between C sequestration efficiency and initial SOC content has been reported, mainly because SOC tends to increase faster if initial SOC content is far from its saturation level. C sequestration efficiency of most of the studies used was lower than 50 %. For instance, after 29 years, the C sequestration efficiency after application of pig and cattle manure and wheat straw ranged between 11 – 17 % in a Vertisol cultivated by a soybean-wheat rotation (Hua et al., 2014). Triberti et al. (2008) found C sequestration efficiencies between 3.7 and 8.1% in a maize-wheat rotation after applying organic amendments. The unrealistically high C sequestration efficiency in the examined studies of our analysis could be due to four major reasons: (i) Uncertainties in the quantification of annual entry of some of the organic C inputs and lack of quantification for others. These uncertainties are quite common to many long-term field studies. For CC and CMP managements, only aboveground biomass of the unseeded or seeded plant cover were recorded or estimated; in some studies it was quantified on only one occasion. The C input *via* roots of the plant cover might represent a significant input of C which was not taken into account in the examined studies. Guzmán et al., 2014 found a root/shoot ratio of 0.8 (about 44% of the organic C in the biomass belongs to the belowground biomass) for cover crops, and also Ludwig et al. (2007) estimated an incoming organic C through the rhizodeposition process of 50% of the organic C content of the incoming biomass. (ii) Inaccuracies in the estimation of SOC stock (Aguilera et al., 2013). SOC stocks calculations require the measurement of soil bulk density, and in some of the studies soil bulk density was estimated but not experimentally calculated. Moreover, changes in bulk density lead to changes in sampled soil mass when a fixed sampling depth is used, possibly biasing the results. (iii) Positive feedback between the incoming organic C and the improvement of soil fertility features, which might reduce SOC oxidation and increase SOC protection mechanisms of the native SOC. (iv) RMPs (such as organic amendments, plant or pruning debris cover) tend to decrease soil loss, and therefore SOC, by erosion. For instance, in experimental olive plots with a relative low slope (about 4%), Gómez et al. (2011) found soil losses about 2.6 t ha^{-1} yr^{-1} under conventional tillage, whereas for those plots under vegetation cover this value was one order of magnitude lower (0.17 t ha^{-1} yr^{-1}), in a relatively rainy year (845 mm).

Furthermore, when organic materials, such as manure, compost and by-products of the olive oil and wine industries, are added to the soil, at least a share of their organic C is decomposed producing CO_2, while another part is sequestered in the soil. Increase in the SOC pool in the 0–0.3 m depth after long-term use of manure when compared with chemical fertilizers was 10 percent over 100 years in Denmark (Christensen, 1996), 22 percent over 90 years in Germany (Korschens and Muller, 1996), 100 percent over 144 years at Rothamsted, United Kingdom (Jenkinson, 1990) and 44 percent over 21 years in Sweden (Witter et al. 1993). Triberti et al. (2008) reported that 29 years after the start of a trial comparing different off-farm organic amendments, the cattle manure gave the quickest organic C stock build-up: 0.26 t organic C ha^{-1} yr^{-1}. In another study, about 25 and 36 % of applied manure and compost C remained in the soil after 4 years of application, indicating greater C sequestration efficiency with composted than non-composted manure (Eghball, 2002). Annual off-farm organic amendments Zhang et al. (2010) encouraged significant SOC increase of about 7–45% after 25–28 years compared with the mineral fertilizer treatments, with a sequestration rate of about 0.70 to 0.88 t ha^{-1} yr^{-1}. Recently, Hua et al. (2014) found a linear relationship between off-farm organic C inputs (from 0.5 to 7.0 t ha^{-1} yr^{-1}) and SOC sequestration, although a linear relationship is not always observed (see for example Stewart et al., 2009 and Chung et al., 2009)

3.3 *C sequestration rate in the 3 types of fruit tree orchards and under RMPs management*

The effects of RMP management on C sequestration were only evaluated on olive orchards and vineyards, due to the lack of sufficient comparative data for almond orchards. The C sequestration rates in olive orchards were as follows: OA>CMP>CC (5.36, 3.33, and 1.10 t C ha^{-1} yr^{-1}, respectively) (figure 3a). The relatively large differences among management types, although with mean values with a wide dispersion which prevented statistical significance from being determined, were not found for vineyards, where C sequestration rates under the different management practices were relatively similar and not significantly different: CC>OA>CMP (0.78, 0.65 and 0.34 t C ha^{-1} yr^{-1}, respectively) (figure 3b).

In all cases, C sequestration rates were the highest for olive orchards, especially for OA and CMP managements. These differences were due to two main factors. Firstly, the mean annual rate of application of organic amendments to olive orchards was more than 25 times higher than that of vineyards. Secondly, the area covered by plant cover in olive orchards is much higher than in a vineyard, and thus aboveground and belowground biomass is expected to be much higher.

In the case of almond orchards, the C sequestration rate was 2.04 t C ha^{-1} yr^{-1} for CC management (n = 6) (figure not shown). For the rest of the management types it was not possible to assess the C sequestration rate due to the low number of available comparisons. This value is about 1.9 times that of the olive orchards and 2.6 times that of vineyards. Nevertheless, more studies should be carried out with cover crops in almond orchards to obtain consistent results.

Smith (2004) estimated with relatively high uncertainty the potential SOC sequestration for European croplands, mainly for herbaceous crops, according to different managements. For example, in the case of the organic farming the potentially SOC sequestration rate would be between 0 and 0.54 t C ha^{-1} yr^{-1}, for the use of animal manure was about 0.38 t C ha^{-1}, whereas with the use of cereal straw it was about 0.69 t C ha^{-1} yr^{-1}. Zero tillage potential SOC sequestration was about 0.38 t C ha^{-1} yr^{-1}, whereas for reduced tillage, this value was lower. Comparing these results for herbaceous crops with those obtained in our study, for olive orchards the C sequestration rate was about one order of magnitude higher after the use of organic amendments, whereas it was about 1.7 times for vineyards. In the case of SOC sequestration for CC management, the values estimated by Smith (2004) were in most cases lower than those obtained in this study for olive orchards, vineyards and almond orchards. Triberti et al. (2008) found in soils under a maize-wheat rainfed rotation C sequestration, rates between 0.16 and 0.26 t C ha^{-1} yr^{-1} by using residues, slurry and manure. Again, these values in herbaceous cropping systems are lower than those we found in woody cropping systems. The relatively high annual dose of organic matter application in treated woody crops, the implementation of cover crops, where residues are left annually on the soils, and the lower soil perturbations of woody crops, especially in olive orchards, compared to herbaceous crops, might explain the higher C sequestration rate.

3.4 *Influence of duration of the experiment on C sequestration rate for CC management*

The average of soil C sequestration rates for studies with duration of less than 6 years, between 6 to 10 years and higher than 10 years were significantly higher than zero. On average, soil C sequestration for the studies with a duration of less than 6 years was 1.22 t C ha^{-1} yr^{-1}, a figure which was 1.7 times higher than that observed in studies carried out during 6 to 10 years (0.72 t C ha^{-1} yr^{-1}) (figure 4). Higher C sequestration rates in studies with a duration of less than 6 years were not unexpected, since changes in SOC are projected to be faster just after a change in a management practice, and decline thereafter until a new equilibrium is reached some time later (Smith, 2005). For instance, West and Post (2002) found that the majority of SOC change in response to a change to no tillage occurred within the first 10 to 15 years following the implementation of this practice, and Rui and Zhang (2010) found that there was a negative correlation between soil C sequestration rate and duration of soil C sequestration. Finally, Poeplau and Don (2015) found an average C sequestration rate of 0.23 t C ha^{-1} yr^{-1} during the first 54 years after a change in the management, but an average of 0.11 t C ha^{-1} y^{-1}, thereafter reaching the new equilibrium (steady state) after 155 years following the adoption of the new management. Thus the soil C sequestration and soil C efficiency reported in this study should be treated with caution, as the experiment duration in about 44 % of the studies of this meta-analysis was lower than 6 years.

Soil C sequestration rates for studies longer than 10 years, tended to be higher, although differences were not significant, than that of studies between 6 to 10 years of duration. However, caution should be applied as the number of studies of a duration of more than 10 years is scarce (n = 7) and with wide confidence intervals due to the high dispersion of the data.

3.5 *Influence of Mediterranean sub-climates on C sequestration rate for CC management*

Soil C sequestration rate under CC management varied according to the sub-climates of the studies. Values averaged 1.18, 1.22 and 1.27 t C ha^{-1} yr^{-1} for Cfb, Csb and Csa sub-climates, respectively. Averages of soil C sequestration rates of studies under B-type climates (semiarid to arid) were 0.39 t C ha^{-1} yr^{-1} and 0.53 t C ha^{-1} yr^{-1} for BWh and Bsk, respectively (figure 5), but these were not significantly higher than zero. In general, it is acknowledged that the C sequestration potential of semiarid to arid soils is relatively low, because of water and edaphic limitations such as fertility, and chemical (i.e. sodicity and acidity) and physical constraints (Post et al., 1996). Soil C storage is controlled by a series of hierarchical processes, including C inputs and outputs. For example, the upper limit of C input to the soil is determined by net primary productivity of plants, which is in turn constrained by solar radiation, climate, and limitations in soil water and nutrients. Thus, the lower soil C sequestration measured in olive and almond orchards and vineyards on semiarid to arid climates was likely due to the fact that crop productivity in these dry locations is low, and thus so is the annual rate of organic amendments. In addition, C inputs throughout the above and belowground biomass of the plant cover under these climates is expected to be low, and thus so is the soil C sequestration rate.

4. Conclusions

Specific recommended management practices (RPMs) increased C sequestration in Mediterranean olive and almond orchards and vineyards compared to conventionally-managed cropping systems. Nevertheless, soil C sequestration was highest when applying organic amendments due to the relatively high annual doses of organic material applied, especially in olive orchards (e.g. pruning debris, composted olive mill pomace). However, the plant cover management, used as green manure, amounted lower values of SOC sequestration rates, but the importance of this management is that it is relatively easy to be implemented by farmers, and with a relative low cost for farmers. Therefore, a combination of a plant cover in the inter-row of orchards with the application of external organic amendments (e.g. compost) or crop residues (e.g. pruning debris) would be a suitable management. Furthermore, the SOC sequestration would be higher during the first years after implementing the RMPs. Therefore, we recommend that future researches consider different time intervals for the estimation of soil C sequestration. Overall, this research shows that the relatively high sequestration rate combined with the relatively large spatial extent of these cropping systems areas allows the conclusion that the adoption of RMPs is a sustainable and efficient measure to mitigate climate change.

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Table 1. Description of the three managements studied in the meta-analysis. The management type is the result of combining an organic carbon input and a tillage practice.

Management Type	**Description**	**Observations**	**C Input Type**	**Description**	**Tillage Type**	**Description**
CONV	Conventional management	Used as a control. Management included T or NTH with none C input.	None	No organic C input	T	- Tillage with herbicides - Frequent tillage without herbicides
CC	Cover Crops	Cover crop or natural plant cover, which were eliminated by a combination of NTM and NTG or with a RT	CC	- Cover crop - Natural cover of resident vegetation	RT	Reduced tillage. Usually once in spring and once in autumn
OA	Organic amendment	Annual organic amendment consisting in compost, manure, olive mill waste, sewage sludge or CR. Soil were T or NTH.	CR	Crop residues (e.g. pruning debris)	NTH	No tillage with pre-emergence herbicides
CMP	Combined management practices	CC + OA/CR + RT/NTM/NTG	OA	- Manure - Olive mill waste - Sewage sludge - Other	NTM	- No tillage mowing - No tillage with post-emergence herbicides in spring
					NTG	No tillage with grazing. Implies small amounts of manure

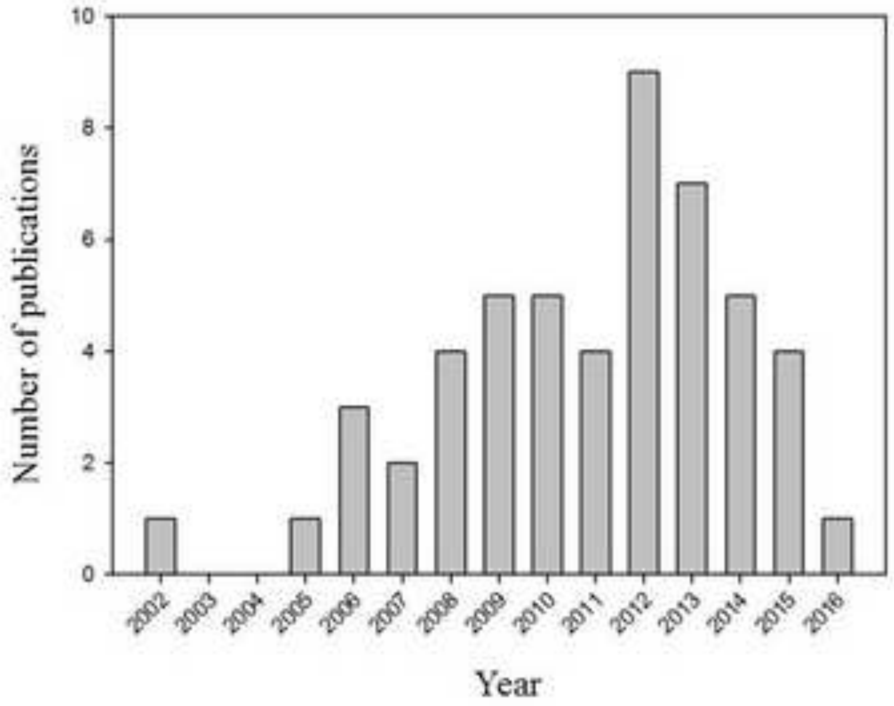
Table 2. The four variables assessed in the study (management, species, duration and sub-climate) and their different categories.

Variable	**Categories**
Management	OA (organic amendments: compost, manure, crop residues, sewage sludge, other)
	CC (cover crops/seeded cover, natural plant cover/unseeded cover)
	CC + OA = CMP (combined management practices)
	None
Tree species	Olive orchards
	Vineyards
	Almond orchards
Duration	Short term (< 6 years)
	Medium-term (6 – 10 years)
	Long-term (> 10 years)
Mediterranean Sub-climates according to Köppen-Geiger classification (main climate, precipitation, temperature)	Csa (Warm temperate, dry summer, hot summer)
	Csb (Warm temperate, dry summer, warm summer)
	Cfb (Warm temperate, fully humid, warm summer)
	Cfa (Warm temperate, fully humid, hot summer)
	BWh (Arid, desert, hot arid)
	BSk (Arid, steppe, cold arid)

Table 3. Effect size, description and equations used for their calculation

Effect size	**Description**	**Equation**
SOC response ratio	Shows the variation in the SOC content in the RMP relative to the CONV management. If > 1 the RMP increases the SOC, if < 1 it decreases it.	1,2
C sequestration rate	Shows the variation per unit of time (year) in the SOC stock in the whole profile in the RMP relative to the CONV management. If > 0 the RMP increases the SOC stock, if < 0 it decreases it.	3,4,5
C sequestration efficiency	Shows the percentage of the incoming organic C that is fixed into the soil after the implementation of the RMP.	6

RMP = Recommended management practice; CONV = Conventional management; SOC = Soil organic carbon; C = Carbon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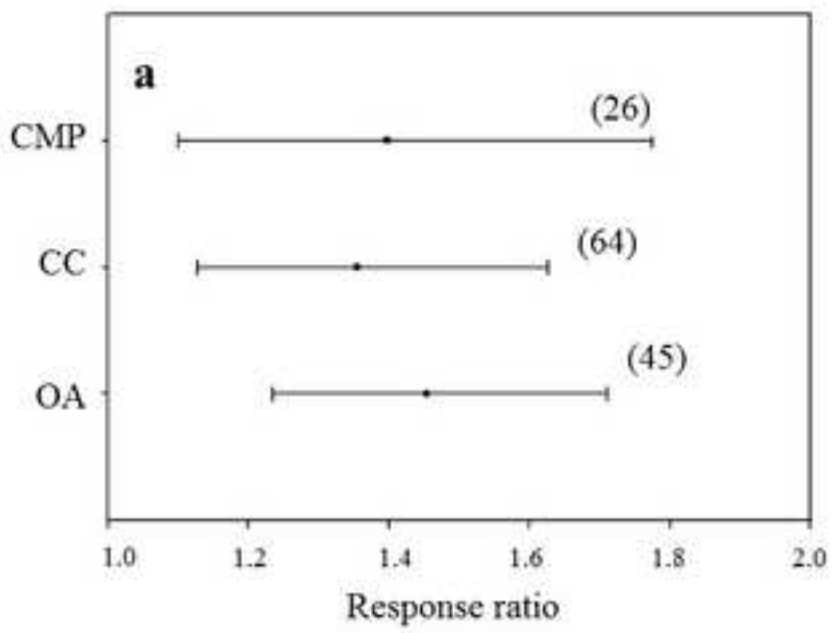
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CC
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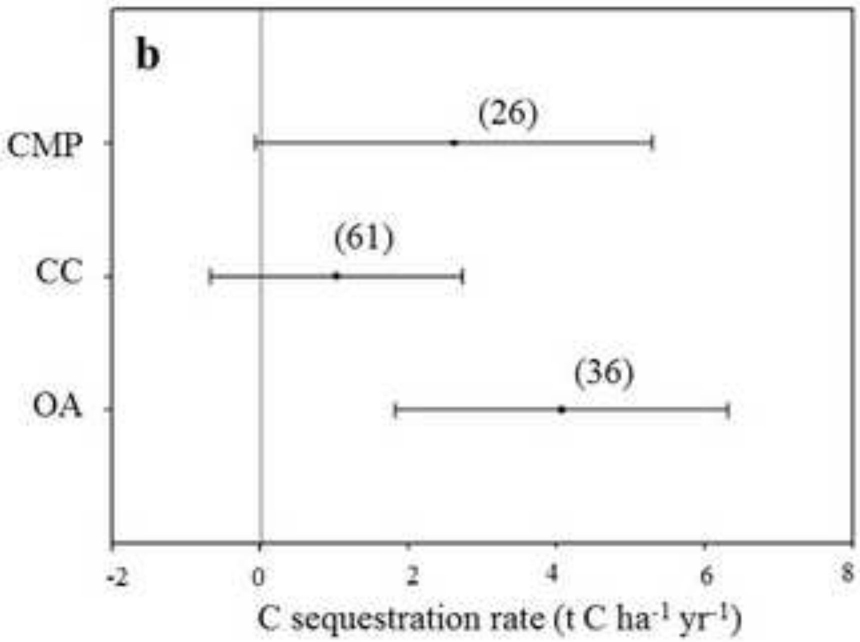
Response ratio


b
CMP
CC
OA
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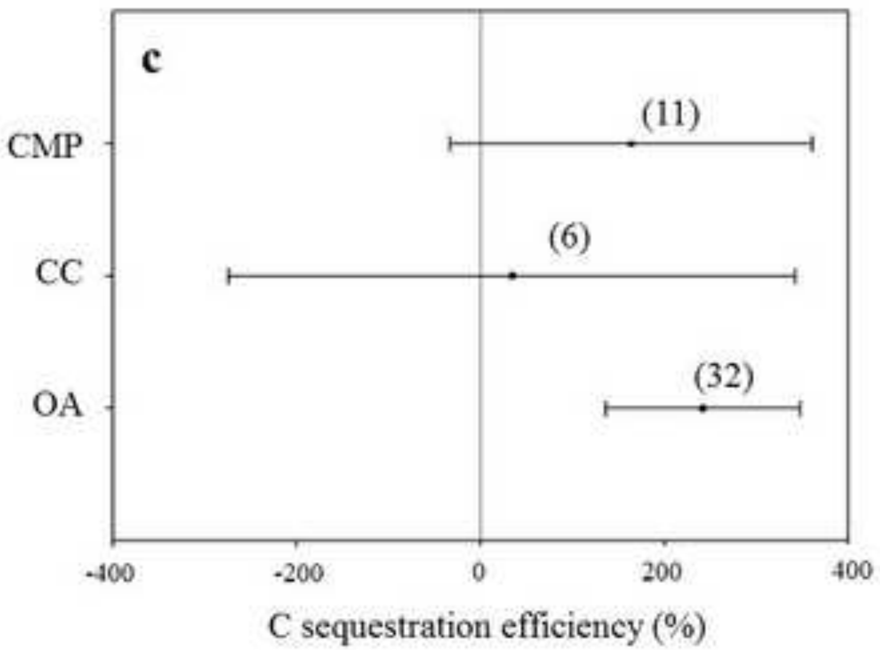
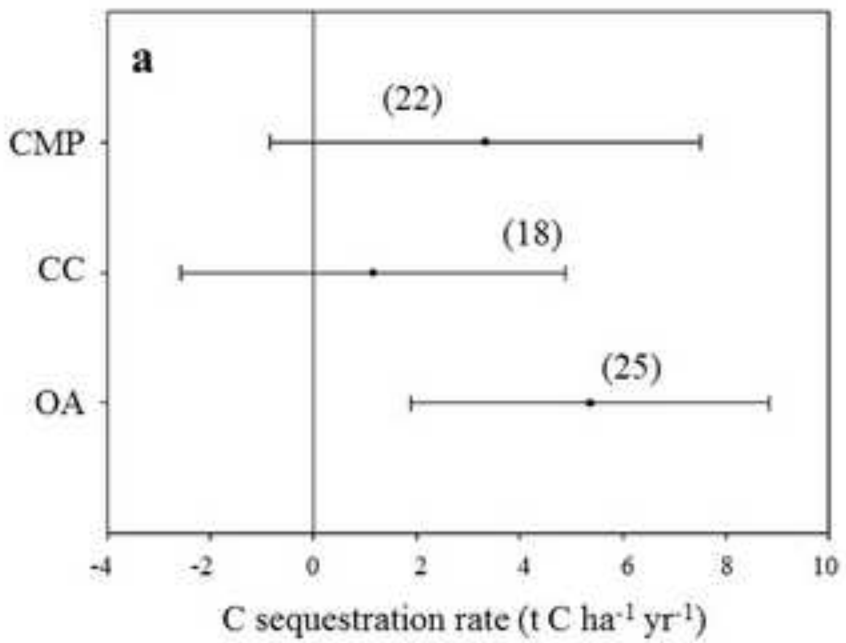
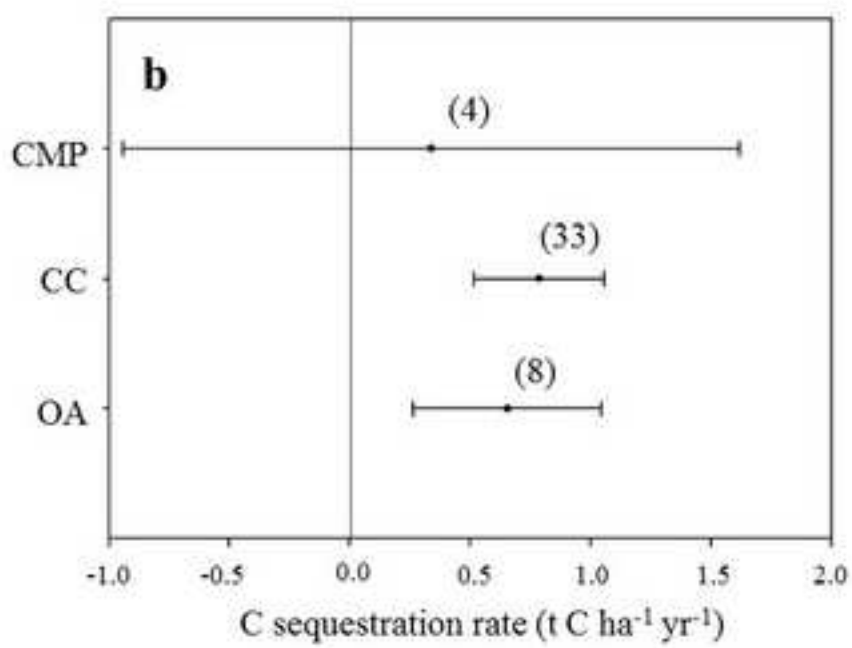
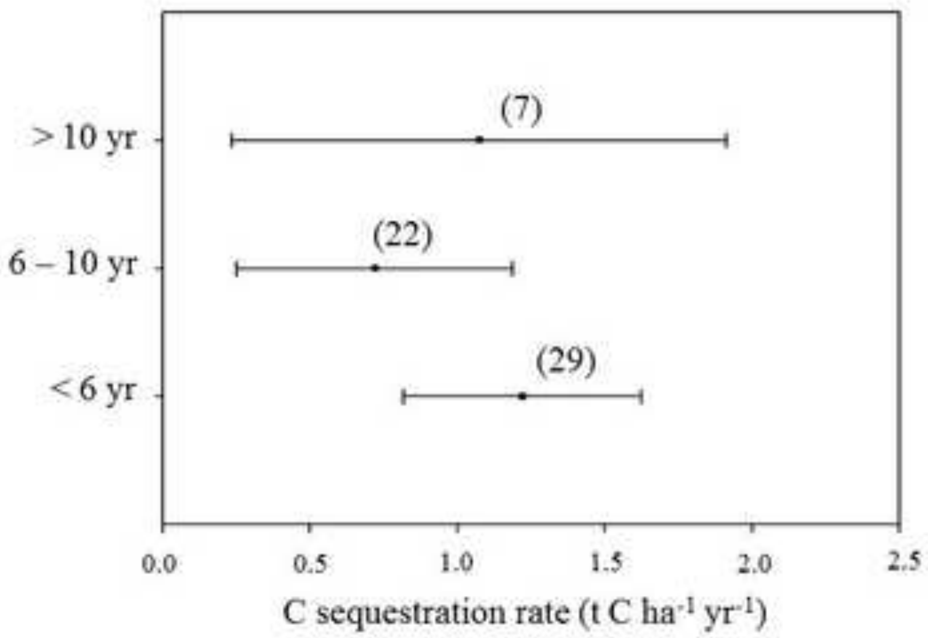
(36)
-2
0
2
4
6
8
C sequestration rate (t C ha-1 yr-1)

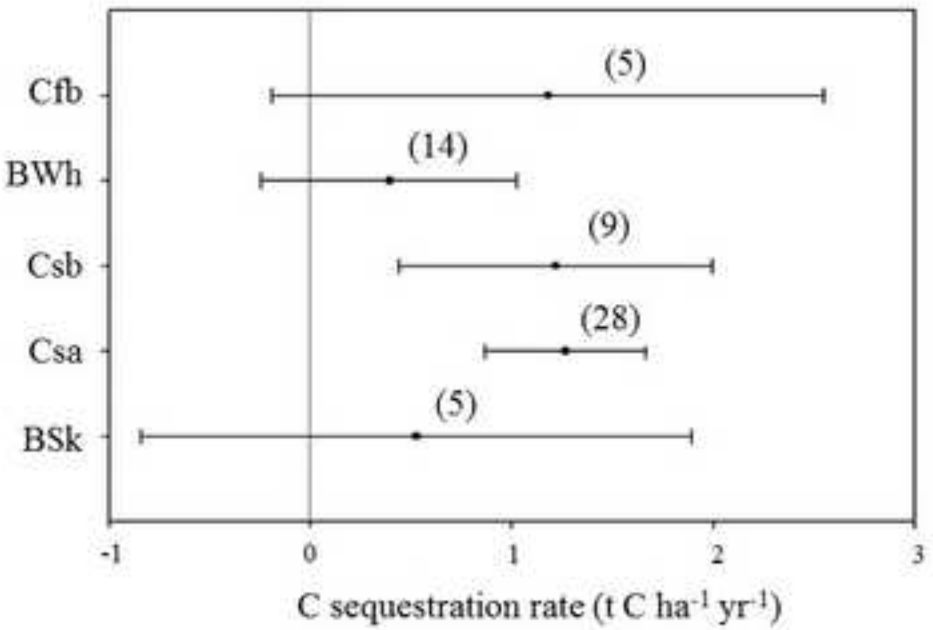

c
CMP
CC
OA
(11)
(6)
(32)
-400
-200
0
200
400
C sequestration efficiency (%)


a
(22)
CMP
(18)
CC
(25)
OA
-4
-2
0
2
4
6
8
10
C sequestration rate (t C ha-1 yr-1)


b
(4)
CMP
(33)
CC
(8)
OA
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
C sequestration rate (t C ha^{-1} yr^{-1})


(7)
(22)
(29)
> 10 yr
6 – 10 yr
< 6 yr
0.0
0.5
1.0
1.5
2.0
2.5
C sequestration rate (t C ha^{-1} yr^{-1})

Figure



Cfb
BWh
Csb
Csa
BSk
(5)
(14)
(9)
(28)
(5)
-1
0
1
2
3
C sequestration rate (t C ha-1 yr-1)