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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.

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

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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 RMPs 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, Gómez 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