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Shifts in soil structure and soil organic matter in a chronosequence of set-aside fields

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ABSTRACT

Set-aside is a commonly used practice worldwide to improve soil quality and fertility. However, the benefits of set-aside have not been quantified in a detailed manner and particularly in semi-arid environments where primary production, and hence C inputs to the soil, is constrained by water availability. Using a chronosequence of set-aside fields (0, 6 and 50 years), data were collected regarding the soil structure, addressed with the distribution of aggregate size classes, soil organic carbon (SOC), and total nitrogen content at the surface soil layer (0–15 cm). Soil structure showed a rapid recovery in the 6-years set-aside field and approached the levels of 50-years set-aside field. The recovery of soil structure, however, was not accompanied by a significant increase in bulk soil or in any aggregate size class SOC. In the 50-years set-aside field, the SOC content was 62% higher compared to the 0-years and 6-years set-aside fields. In this field the SOC content reached identical contents in all aggregate size classes except for the silt-clay fraction. In the latter, lower SOC content was assessed which did not differ from the 0-years and 6-years set-aside fields. In a following step, the Carbon, Aggregation, and Structure Turnover (CAST) model was employed to simulate the evolution of soil structure and C sequestration with time. Overall, the CAST model successfully simulated the evolution of soil structure and SOC stocks and provided critical information about the time required to approach the optimum thresholds under the prevailing environmental conditions. The estimated low rates of C sequestration question the effectiveness of the set-aside practice to restore soil fertility in semi-arid environments. These findings outline the need to evaluate additional practices and/or combinations of practices (e.g addition of organic amendments) to improve its effectiveness. Future work should aim to evaluate such practices considering climatic constraints and soil properties.

1. Introduction

Soils in (semi)-arid climates are characterized by low soil organic carbon (SOC) content that renders them particularly vulnerable to further degradation and fertility loss (Lal, 2004). The low inputs of organic-C, the intense soil management practices (tillage), and the high rates of erosion are recognized as the major factors constraining SOC accumulation and degrading soil quality in semi-arid ecosystems (Moraetis et al., 2015). Thus, the adoption of soil management practices that stimulate SOC accumulation are of paramount importance to prevent further deterioration of soil quality and to maintain their productivity in the long term (Lal et al., 2015).

Agricultural practices aiming to protect and promote soil structure development, like minimum or no-tillage have been associated with gains in C sequestration by several studies across the world (Lal et al., 2015). The positive effect of soil structure on C sequestration has been explained by the physical protection of SOC from decomposition that arises from the compartmentalization of SOC, microorganisms, and exoenzymes (Lutzow et al., 2006; Dungait et al., 2012). The magnitude of C sequestration varies substantially across different sites and this variance has been partitioned to climatic conditions, soil properties, crops, management practices, and the time elapsed since the adoption of the restoration practices (Six et al., 2002b; West and Post, 2002; Lal et al., 2015; Gregorich et al., 2016; Han et al., 2016). Compared to other climates, a limited number of studies has dealt with the interactions of soil structure and SOM in soils evolved in semi-arid environments (Fuentes et al., 2012; Lopez-Bellido et al., 2017). Lopez-Bellido et al. (2017) reported no-tillage as a key practice for improving C sequestration in a semi-arid Vertisol in the Mediterranean and this positive influence was mainly attributed to the encapsulation of C and N within microaggregates. Critical questions, however, remain yet unanswered including the effect of natural restoration on soil structure development and its potential feedbacks with C sequestration, the influence of soil physical and biochemical properties as well as the time

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required to reach the optimum levels of soil fertility depending on the prevailing environmental conditions. Regarding the latter, our knowledge has been limited until recently due to the lack of appropriate tools which account for the influence of soil structure, primary production, and soil properties on SOC turnover (Malamoud et al., 2009; Segoli et al., 2013; Stamati et al., 2013). The soil Carbon, Aggregation, and Structure Turnover (CAST) model is based on the aggregate hierarchy concept (Stamati et al., 2013) and has been successfully used to simulate soil structure and SOC interactions in sites with disparate climatic and edaphic conditions (Giannakis et al., 2014; Panakoulia et al., 2017).

Soil conservation practices and the C inputs from primary production stimulate the sequestration of C to the soil. There is, however, evidence that the combined effect of these processes is non-linear and depends on the state of physical structure and the amount of C inputs (Kong et al., 2005; Reinhart and Vermeire, 2016; Wiesmeier et al., 2016). Understanding, thus, the feedbacks between soil structure and C inputs remains a critical issue for planning appropriate management practices and maximizing their effectiveness regarding the C sequestration. We, thus, hypothesized that if the disrupted physical structure, due to tilling, constrains the C sequestration in the Mediterranean landscapes, then a rapid accumulation of C would occur shortly following the adoption of restoration practices. By contrast, if C input is the limiting factor, then both physical structure and SOC would not or would slowly respond to the adopted practices. To shed light on the interactions between soil structure and C sequestration under Mediterranean conditions a chronosequence of adjacent fields subjected to set-aside practice for different periods of time (0, 6 and 50 years) was selected. The soil in each field was investigated for the distribution of aggregate size classes and basic soil chemical properties. To our knowledge, this study is one of the few which have employed a chronosequence of fields to get insights on the potential of agricultural practices (set-aside, no-tilling) to stimulate natural restoration processes under Mediterranean conditions (Álvaro-Fuentes et al., 2014). Finally, the CAST model (Stamati et al., 2013) was employed to determine the time for soil structure restoration and to evaluate the evolution of C sequestration for a period of 100 years.

2. Materials and methods

The study area is located at the prefecture of Heraklion in Crete, and has an elevation of approximately 600 m. The area has a semi-arid climate with annual mean precipitation and temperature 654 mm and 17.3 °C, respectively. A chronosequence of soils differing in the duration of set-aside practice was examined in the present work. The close vicinity of the selected fields minimized the variance of climatic conditions and soil properties and allowed for the accurate estimation of the effect of the set-aside practice on soil fertility restoration. The first field was a vineyard subjected to tillage, twice per year, for more than 30 years and receiving conventional fertilization early in the growing season (typically during March). The second field was a vineyard of the same age that had been abandoned (not subjected to tillage and fertilization) the last six years. The last one was an uncultivated field for 50 years that was dominated by annual grasses and subjected to restricted grazing.

2.1. Soil physical and chemical analyses

Soil samples were taken three times from each field, between the end of March and May 2015 from the upper 15 cm of the fields. Particle size analysis was carried out by the Bouyoucos hydrometer method (Bouyoucos, 1962). The soil in the study area was characterized as clayey with clay and silt content 53.0 ± 1.2% and 35.7 ± 1.7%, respectively with slight variations between fields (Table 1). The bulk density (BD) of the soils was determined by drying undisturbed soil cores of known volume at 105 °C to a constant weight. The distribution of water-stable aggregates (WSA) among various size classes was performed by wet-sieving adopting the protocols developed by Elliott (1986) and Cambardella and Elliott (1993). Before sieving, small rocks and plant-origin debris were manually removed from the samples followed by air drying at 45 °C for 48 h. Briefly, 100 g of dried soil was placed in a 2000 μm sieve and was sunk into water for 60 times. The soil fraction passing the screen was placed in a 1000- μm sieve and was sunk into water for 40 times. The same procedure was repeated with a 250-μm and a 53-μm sieve for 20 and 10 times, respectively. The fraction < 53 μm was collected through centrifugation. The aggregate size classes were subjected to sand correction according to the methodology developed by Elliott et al. (1991).

The SOC and TN contents were measured in an elementary analyzer (Analytik Jena Multi N/C 2100S). Ammonium (NH_4^+-N) and nitrates (NO_3^--N) were extracted with 2 M KCl and 0.01 M $CaCl_2$, respectively. Then, they were measured colorimetrically in a Perkin-Elmer spectrophotometer (Lambda 25) with the Nessler reagent and the Cd-reduction method, accordingly.

2.2. The CAST model

The CAST model is a mathematical model that simulates the mechanisms of aggregate and carbon turnover (Stamati et al., 2013). It has been built on the concept of aggregates (de)formation introduced by Tisdall and Oades (1982). The CAST model postulates that micro-aggregates are formed within the macro-aggregates and considers three main aggregate size classes: i) the macro-aggregates (AC3: > 250 μm), ii) the micro-aggregates (AC2: 53–250 μm) and iii) the silt-clay sized aggregates (AC1: < 53 μm). The plant residues entering the soil are colonized by microbial decomposers which stimulate the formation of macro-aggregates around particulate organic matter (POM). Further decomposition of POM results in the formation of micro-aggregates within the macro-aggregates by encapsulating the finely fragmented POM in silt-clay sized aggregates. The incorporated organic matter is subjected to further decomposition and as consequence, the microbial activity decreases gradually. With the progress of time, the stability of macro-aggregates weakens due to the depletion of microbial-origin polymers that are responsible for the binding of the structural components of macroaggregates. The unstable macro-aggregates are sensitive to slaking events, which leads to their disruption and the simultaneous release of stable microaggregates and silt-clay sized aggregates.

The C pools of the Roth C model (Coleman and Jenkinson, 1996) are also considered in the individual aggregate size classes of the CAST model. These include the decomposable plant material (DPM), the resistant plant material (RPM), the microbial biomass (BIO), the humified organic matter (HUM), and the inert organic matter (IOM). From the above-mentioned C pools, the AC1 aggregates include BIO, HUM, and IOM, the AC2 aggregates include BIO, HUM, IOM, and fine DPM and RPM, and the AC3 aggregates include BIO, HUM, IOM, and fine and coarse derived DPM and RPM. The decomposition of each C pool is described by a first-order kinetic that produces CO_2, BIO, and HUM. The proportion of C that is transformed to CO_2, BIO and HUM is determined by the soil clay content (Coleman and Jenkinson, 1996). All the abbreviations reported in the previous paragraphs are summarized in Table 2.

The CAST model requires also inputs of climatic conditions, aboveground plant-derived C, and basic soil properties (particle size distribution, BD, soil depth) (Stamati et al., 2013). In addition, the model requires data for the mass distribution of WSA in the size classes reported previously (AC1, AC2, AC3) and their SOC content. The aggregate size classes used in the simulations have been corrected for the sand content since sand does not correspond to real aggregates (Elliott et al., 1991). All this information is summarized in Table 1 and Table 3. The parameters used for model calibration, like decomposition rates of the different C pools, rates of macro- and micro-aggregate formation, proportional contribution of the components (DPM, RPM, AC1 and