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Carbon input threshold for soil carbon budget optimization in eroding vineyards

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ABSTRACT

Previous studies have documented that, relative to conventional tillage (CT), alternative soil management (reduced tillage, mulching, or cover crops) decreases soil erosion and increases soil organic matter (SOM) in vineyards. These previous studies, however, failed to consider the loss of soil organic carbon (SOC) with erosion that could occur with the adoption of agro-environmental measures (AEM) in a semiarid environment. Accordingly, the aims of this study were to determine whether changes in SOC content under AEM management are always positive and to develop a conceptual model for estimating the "SOC threshold". The SOC threshold was defined as that level of SOC in an AEM-managed vineyard above which erosion will result in greater loss of C than occur in a comparable vineyard with CT management. SOC was analyzed at a 100 paired sites (vineyards with AEM management vs. CT). The results showed that in some cases the loss of C was higher with AEM than with CT. Overall, the results indicate that the SOC threshold may be a key parameter in determining the best AEM measures for vineyards that are on slopes and therefore vulnerable to erosion.

1. Introduction

Soil erosion is a problem in vineyards because it reduces soil fertility, damages nearby roads, and causes floods, (Costantini et al., 2015; Lieskovský and Kenderessy, 2014; Martínez-Casasnovas et al., 2015; Vaudour et al., 2015). Higher erosion rates have been recorded in vineyards than in other land use areas (Cerdan et al., 2010) in the Mediterranean region (Vanmaercke et al., 2011) because of several characteristics of the soil, climate, topography, soil management and the vines are planted and cultivated along the slope (Novara et al., 2011; Tarolli et al., 2015). First, the soil in traditional Mediterranean vineyards is bare for most of the year; the cover is only significant during the summer, when there is almost no rain other than sparse and irregular storms. Bare soils result in high erosion rates, and a recovery of the vegetation contributes to an important reduction of soil and nutrient losses in the Mediterranean region (Cerdà, 1998; Novara et al., 2013, 2015) and Africa (Mekonnen et al., 2015). Second, traditional soil management in Mediterranean vineyards includes continuous tillage with the goal of eliminating competition between vines and other plants for water and nutrients. Although tillage also reduces evaporation in the Mediterranean region, it results in high erosion rates (García-Orenes et al., 2012). Third, a high soil organic matter content can help reduce erosion, but soils of the Mediterranean vineyards have low organic matter content because of the low inputs of organic matter and because the climate promotes high mineralization rates. The organic matter content is further reduced by the tillage. Fourth, vineyard soils in many regions are shallow and with low infiltration rate, which increases their vulnerability to soil erosion. Finally, the large vine-producing regions in the Mediterranean region are hilly and experience high intensity rainfall events, both of which will obviously increase the potential for erosion (Cerdà et al., in press).

Within this context, alternative management, such as reduced tillage, the application of mulch, or the planting of cover crops, has been developed to protect soil from erosion. These alternative management methods generally increase the input of soil organic matter (SOM) (Prosdocimi et al., 2016; Brevik, 2013). The importance of SOM in reducing soil erosion is well known, i.e., SOM reduces erosion by improving soil structure, hydrological characteristics, aggregate stability and resistance. (Balesdent et al., 2000; Barthès and Roose, 2002; Six et al., 2004). Erosion rates are lower and SOM contents are higher in vineyards that are planted with cover crops and are not tilled than in vineyards that are managed with bare soil and traditional tillage (Biddoccu et al., 2014; Ruiz-Colmenero et al., 2013; Virto et al., 2012). Hence, the adoption of soil-conservation practices is encouraged both to prevent erosion and to sequester atmospheric carbon dioxide (CO_2) in the soils. As a consequence of the 1992 reforms of the Common Agricultural Policy in Europe, agro-environmental policies have been developed through

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payments to farmers in order to improve environmental protection. In Mediterranean countries, the payments are especially desirable because some agro-environmental measures (AEM) could reduce agricultural production and therefore farmer profit (Ruiz-Colmenero et al., 2011). A main objective of the second axis of the Rural Development Program of the European Union (Council Regulation EC No 1698/2005) is the improvement of the environment and the countryside, and the program encourages soil management with cover crops to reduce erosion (Article 4, EC No 1698/2005). This can be done through the previously mentioned AEM payments, which will be provided to growers whose management results in positive environmental outcomes.

Although agricultural conservation practices, including the planting of cover crops, are included in the AEM, few studies have analyzed the carbon (C) cycle under erosion processes with alternative soil management. The apparently positive effect of higher soil C content on soil properties and climate change mitigation could lead to C loss in the system in terms of higher CO_2 emissions or higher amounts of C in soil sediments that are transported from the field by erosion. Gao et al. (2012, 2013) introduced the C health threshold theory, which indicates that increases in soil C levels could lead to ecosystem degradation. Gao et al. also determined that if C storage exceeds nutrient and water supply limits, an ecosystem will fall into a sub-health state of fitness; after that, C will be lost through soil erosion or other pathways. In the current study, the SOC threshold is defined as that level of SOC in an AEM managed vineyard above which erosion will result in a greater loss of C than occur in a comparable vineyard that is managed with conventional tillage (CT). Several authors have studied the C health threshold theory with respect to afforested and natural soils (Gao et al., 2012; Wang and Cao, 2011), but the theory has not been investigated in a semiarid cultivated soil.

This paper attempts to answer three questions with respect to vineyards located on hillsides in the semi-arid environment of the Mediterranean region: i) given that substantial C may be lost via erosion, is it always desirable to increase the SOC content of the soil?; ii) can the SOC stock be increased under AEM without resulting in high C loss due to erosion? and iii) is the SOC threshold measurable?

1.1. The SOC threshold concept

Erosion results in C loss via three major pathways: (i) C contained in soil that is transported and deposited elsewhere as sediment; (ii) dissolved organic carbon (DOC) contained in runoff; and (iii) CO_2 emission (Jacinthe and Lal, 2001). Among these pathways, the first is most important, because the most C is lost as SOC in sediment. The other two pathways, although relevant for the global C budget and for ecological properties, are dependent on sediment transport and C content. Using data for SOC stocks and dynamics from long-term experiments (more than 7 years) in different regions, Jacinthe and Lal (2001) found that erosion-induced CO_2 emission rates ranged from 6 to 52 g C m^{-2} yr^{-1}. Similarly, in a short-term experiment (98 days), Van Hemelryck et al. (2010) estimated that soil redistribution processes resulted in an additional loss of 2 to 12% of C from eroded sediment via CO_2 emission. Both studies showed that erosion induced-CO_2 emission depends on the C content of the soil and sediment. Similarly, the DOC in runoff represents a low percentage of the total C loss (McHunu and Chaplot, 2012). It follows that the quantity of C lost during erosion can be reasonably estimated from the quantity of SOC that is transported with eroded soil and that is deposited elsewhere as sediment.

The loss of C in soil sediments ($OCloss_{sediment}$) can be described by the following linear relationship (Starr et al., 2000):

$$OCloss_{sediment} = SE * SOC * E_r \quad (1)$$

where SOC is the content of organic C in soil (%), E_r is the enrichment ratio of eroded sediment relative to the original soil (dimensionless), and SE is soil erosion rate (Mg $ha^{-1}y^{-1}$). According to Eq. (1), C loss increases with the erosion rate and SOC content. SOC and SE are both functions of organic matter input into the soil, i.e., increases in soil organic matter increase SOC and reduce SE because organic matter increases soil aggregate stability (Loveland and Webb, 2003).

In sloping vineyards, alternative soil management (AEM management, i.e., management without tillage and with a cover crop) reduces erosion relative to conventional tillage (CT) because the cover crop reduces the impact of rain drops on the soil, increase infiltration and dissipation of flow energy, produces biomass that contributes to increases in SOC (Novara et al., 2011) and therefore to aggregate stability (Blavet et al., 2009). The higher SOC level resulting from continuous AEM management, however, produces C-enriched sediments and consequently could lead to higher C losses than with CT, despite the lower SE (Fig. 1). Considering that possibility and as noted earlier, we define the SOC threshold as the level of SOC under AEM management that results in a C loss with AEM management that is equal to the C loss under CT management ($OCloss_{CT}$) (Fig. 1).

If the soil C saturation level (the maximum, steady state level of C that can accumulate in a specific soil) is higher than the SOC threshold, the SOC threshold will correspond to a C_{AEM} value; if the soil C saturation level is lower than the SOC threshold, the SOC threshold will be equivalent to the C saturation value. We indicated C saturation level (or C steady state) as the maximum level of C accumulated in a certain soil, despite the C input increasing.

Considering constant environmental conditions for both soil managements, the SOC threshold is calculated with the following Eqs. (2 and 3):

$$Closs_{AEM} = Closs_{CT} \quad (2)$$

and according to Eq. (1), it follows that:

$$SE_{AEM} * SOC_{AEM} * E_{rAEM} = SE_{CT} * SOC_{CT} * E_{rCT}. \quad (3)$$

Based on Eq. (3), the C losses relative to SOC content with AEM and CT management are presented in Fig. 2 (green and red lines). Considering the same value of SOC (C_1) for CT and AEM, OCloss will be higher for CT ($OCloss_{CT}$) than AEM ($OCloss_{AEM}$), given that the erosion rate SE will be higher in CT than in AEM because of differences in soil cover.

If no change in soil management occurs, the SOC content in CT can be considered constant over many years. Given a value of SOC under CT (SOC_1) with $OCloss_{CT}$, the $OCloss_{AEM}$ will be reached with a SOC content equal to SOC_2. Values higher to SOC_2 will result in a higher OCloss in AEM than in CT. The SOC_2 value can, therefore, be considered the SOC threshold for a given soil that, if managed under CT, will contain a steady state level of SOC equal to SOC_1 (Fig. 2).

2. Materials and methods

2.1. Study area and soil sampling

The study area is located in southern Sicily and is one of the 18 vineyard Controlled Denomination of Origin (DOC) areas on the island (Fig. 3). In the "utilized agricultural area" (UAA) of 11,588 ha, 35.5% is devoted to vineyard cultivation, 32.2% is arable land, and 11.1% is planted with olive trees. The mean annual precipitation is 516 mm. Rainfall is highest in October (monthly mean rainfall of 81 mm) and lowest in July (monthly mean rainfall of 2 mm). On average, 3% of the mean annual rainfall occurs during summer (June, July, and August) while 42% occurs during November, December, and January. The mean annual temperature is 18 °C; the hottest months are July and August (monthly means of 25 °C), and the coldest months are January and February (monthly means of 11 °C). Vineyards in Sicily are commonly managed with CT (at least five shallow tillages per year) to control weeds and reduce water competition. Recently, alternative soil management in vineyards is spreading thanks to AEM. In particular, AEM management in Sicilian vineyards involves annual cover cropping using legumes like faba bean (*Vicia faba*) and vetch (*Vicia sativa*). The cover crop is seeded in autumn and disked into the soil in spring. In summer the vineyard is subjected to two shallow tillages.