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Protection of soil from the loss of organic carbon by taking into account erosion and managing land use at varying soil type: indication from a model semiarid area

Sergio Saia[1*], Calogero Schillaci [2,3], Aldo Lipani[4], Maria Fantappiè[5], Michael Märker[3,6], Luigi Lombardo[7], Maria G. Matranga[8], Vito Ferraro[8], Fabio Guaitoli[8], Marco Acutis[2]

1 [Italy Council for Agricultural Research and Economics (CREA), Cereal Research Center (CREA-CER), Foggia, Italy, sergio.saia@crea.gov.it, *corresponding author]
2 [Department of Agricultural and Environmental Science (DISAA), University of Milan Via Celoria 2, 20133 Milan, calogero.schillaci@unimi.it]
3 [Department of Geosciences, Tübingen University, Germany Rümelinstr 19-23 Tübingen, Germany]
4 [Institute of Software Technology and Interactive Systems, TU Wien, aldo.lipani@gmail.com]
5 [Council for Agricultural Research and Economics (CREA), Centre for Agrobiology and Pedology (CRA-ABP), Florence, Italy, maria.fantappie@crea.gov.it]
6 [Department of Earth and Environmental Sciences, University of Pavia, Italy. Michael.maerker@unipv.it]
7 [Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Tuwal, Jeddah. luigi.lombardo83@gmail.com]
8 [Regional Bureau for Agriculture, Rural Development and Mediterranean Fishery, the Department of Agriculture, Service 7 UOS7.03 Geographical Information Systems, Cartography and Broadband Connection in Agriculture, Palermo, mariagabriella.matranga@regione.sicilia.it, vito.ferraro@regione.sicilia.it]
9 [Regional Bureau for Agriculture, Rural Development and Mediterranean Fishery, the Department of Agriculture, Service 5 UOS5.05 - Valutazione territoriale e gestione del rischio in agricoltura, , fabio.guiaitoli@regione.sicilia.it]

Abstract

Drylands cover nearly of the half of the world and are inhabited by ca. 40 % of the world's population. Such lands harbour a variety of soils whose net primary and agricultural production is limited by water scarcity and high temperatures in the area, and other soil-specific traits, including actual soil erosion. In such conditions, the preservation of the soil organic carbon (SOC) pool has a striking potential to mitigate the loss of fertility and thus yield potential. Here we used a reference semiarid area (Sicily, Italy) for the estimate of the importance of land use and soil erosion potential on SOC variation in space and time.
The most important predictors of SOC concentration were soil texture, land use, valley depth, rainfall, channel network base level. SOC variation in the area strongly depended on the subarea and did not match the SOC at the baseline. The present results can imply both agronomic and policy consequences at the district level and call for an intervention on soil fertility to maintain agriculture productivity. These results can help in calibrating models of SOC dynamic under various management or climate change scenarios.

Keywords: Soil Organic Carbon, Drylands, Worldclim, Soil erosion, Boosted regression trees, geographic information systems, remote sensing.

Introduction, scope and main objectives

Drylands cover nearly of the half of the world and are inhabited by ca. 40 % of the world's population. Such lands, mostly occurring in undeveloped and developing countries, harbour a variety of soils whose net primary and agricultural production is limited by water scarcity and high temperatures in the area, low water holding capacity (WHC) and fertility of the soil and other soil-specific traits, including actual soil erosion. In such conditions, the preservation of the soil organic carbon (SOC) pool, especially in the topsoil, has a striking potential to mitigate the loss of WHC and fertility and thus yield potential, and also increase the CO_2 sequestration ability of the soil. These are further needed at the light of the current climate change, which is mostly harming the fragile (agro-)ecosystems of drylands. It is well known that cultivation have frequently negative effects on SOC accumulation and soil resilience to erosion, desertification and climate change (Kämpf et al., 2016; Novara et al., 2013; Schillaci et al., 2017). This implies that SOC management plays a direct and crucial role in the world economy and is strategic to combat hunger and poverty. A number of agronomical management measures can be adopted to mitigate loss of carbon and preserve soil ecosystem service. The most important of which include land use, land cover, the choice of crop species and genotypes, and soil management techniques, especially tillage. However, the role of each of these techniques and their interaction on SOC concentration, stock and change in space and time appear far to be clarified since it varies with the environmental traits of the site under study and likely with the gross income of the population in the area and nation. In addition, the lack of data from many areas strongly impairs the ability to produce reliable indications on the site-specific management able to preserve SOC and produce stimuli to actual agricultural yield and potential income. In the present experiment, we used a reference semiarid area (Sicily, Italy) for the estimate of the importance of land use and soil erosion potential on SOC variation in time (both as % and absolute compared to the initial) at varying soil type and aridity of the environment. Sicily has great potential as an open laboratory for studies about ecological issues and anthropic pressure on the agro-ecosystems thanks to the variability of its traits and deep knowledge of its soils. Indeed, a total of about 7000 soil samples corresponding to ca. 2700 georeferenced point (more than 1 point each 10 km^2, Fig. 1A) are available, with information on SOC concentration, bulk density and soil texture. In addition, Sicily has variable, but on average high, demographic density and % area cropped in its territory, an ancient environmental and sociological history, a high climatic variability, several land uses and dominations from different populations, which introduced various plant species and management techniques and environmental heritages. The sum of such conditions makes Sicily an open and well suited laboratory to study the impact of anthropic pressure and of environmental variation at large scale (ecosystem level) and micro scale (few squared km), and of land cultivation and management on other environmental traits, including SOC distribution and dynamics.

In particular, we defined and account topsoil SOC changes in the recent time (a 15-years timespan) with the implementation of the digital soil mapping (DSM) algorithm to a legacy dataset.

This will allow to suggest, also on the base of the latest erosion maps, possible interventions such as the application of conservation management techniques or provision of benefits to certain land uses including permanent cropping or reforestation to insure the maintenance of productivity of soils for the next generation.

Methodology

Sicily (Italy) is a semiarid area in the very middle of the Mediterranean Sea. It’s extended 25,286 km^2, 60% of which is cultivated. The Island has a mean annual temperatures of 1.8 °C to 15.0 °C and mean annual precipitation from 350 to 1300 mm. Main annual crops are winter cereals, legumes and a wide range of horticultural crops; the main perennial crops are olive groves, vineyards and fruit trees such as citrus, almonds, stone fruits. Woodlands are mostly anthropic. Adoption of conservative soil management techniques is almost absent. Dominant soils (World Reference Base) are Calcaric Regosols, Haplic Calcisols, Calcic Vertisols, Vitric or Silandic Andosols, Calcaric and/or Mollic Leptosols, Calcaric Phaeozems, and Fluvic Cambisols. Hence it can be considered quite representative of many countries. The Regional Bureau for Agriculture, Rural Development and Mediterranean Fishery, the Department of Agriculture, and Service 7 UOS7.03 provided the dataset used in this study, which included soil texture (by sedimentation method) and organic C concentration in the topsoil (0-40 cm). Meteorological data were drawn from Worldclim (Hijmans et al., 2005), land covers from CORINE of the years 1990 and 2006 at 100-m spatial resolution for the models built for the year 1993 and 2008, respectively (http://land.copernicus.eu/pan-european/corine-land-cover). The analysis was carried out according to arable land (ARA), vineyards, fruit trees and berry plantations, and olive groves (grouped in VFO), annual crops associated with permanent crops, complex cultivation patterns, land principally occupied by agriculture, with significant areas of natural vegetation (grouped in CCP). Remote sensing-derived predictors consisted of the LANDSAT 5 spectral bands and the Normalized Difference Vegetation Index (NDVI) was derived and included as explanatory variable of SOC. Shuttle Radar Topography Mission (SRTM-C) digital elevation model (DEM, September 2014, 1-arcsec spatial resolution) was used for the calculation of the morphometric spatial predictors by means of SAGA GIS. Eleven terrain attributes were calculated: 1) slope, 2) catchment area, 3) aspect, 4) plan curvature, 5) profile curvature, 6) length-slope factor, 7) channel network base level, 8) convergence index, 9) valley depth, 10) topographic wetness index, 11) landform classification. Boosted Regression Trees (BRT, Elith et al., 2008) was used to identify the relationships between SOC and its predictors and to regionalize the SOC (as variation of its concentration and mean amount per soil pixel). Relationships between variables are explained through response curves. We used R program, with the ‘dismo’ package developed by Elith et al. (2008). Finally, the soil erosion risk map by Fantappiè et al. (2015) was compared to the variation of SOC in a 15 years (1993 to 2008) timespan.

Results

We predicted SOC concentration and its variation in time (Fig. 1B) and SOC stock (Fig. 1C) across Sicily, and also estimated the SOC stock and the variation of the SOC concentration for different land covers (Fig. 1D). Annual rainfall, soil texture, land cover (CORINE), and mean annual temperature were the most important predictors of SOC stock. Our prediction ($R^2 = 0.470$) better fitted to the entry data than other wide scale predictions (Global Soil Organic Carbon Estimates, $R^2 = 0.034$; and International Soil Reference and Information Centre Soil Grids, $R^2 = 0.127$). Prediction of SOC concentration showed high accuracy, with pseudo-R^2 higher than 0.693 for the 1993 and 0.634 for 2008 data. The most important predictors of SOC concentration were soil texture, land use, valley depth, rainfall, channel network base level, a measure correlated with the height above the see level [a.s.l.] of the basin upon each pixel and thus to the chance of receiving SOC by erosion, and length-slope (LS) factor, which is correlated to erosion potential of the area. The variation of the SOC in the area under study strongly depended on the subarea within the region and did not match the SOC map at the baseline (1993). Such variation was partly explained by the potential erosion and deposition of soil after erosion.

Maps + chart

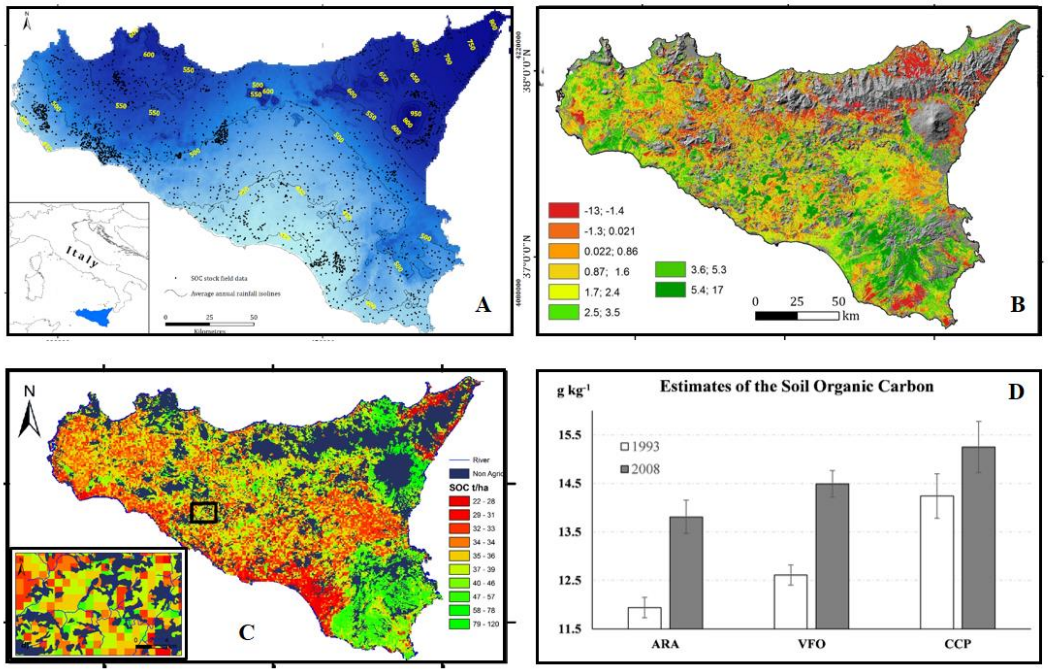

Fig. 1: [A: Locations of the sampling sites in the area under study (Sicily). The mean annual rainfall is shown in mm/year (published in Schillaci et al., 2017). **B:** 100-meters resolution map of the difference in the SOC (expressed in g C kg^{-1}) during the study period. Reddish pixels indicates a loss and greenish pixels a gain in the SOC during time. Grey for non agricultural areas. **C:** 1-km resolution of the SOC stock (expressed in t C ha^{-1}). Reddish pixels indicates low stock and greenish pixels high stock. Grey for non agricultural areas. **D:** SOC concentration (g C kg^{-1}±S.E.) in each of the land use groups used in 1993 and 2008. ARA for arable land; VFO for vineyards, fruit trees and berry plantations, and olive groves; CCP for annual crops associated with permanent crops, complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation.**]**

Discussion

The mean prediction of the SOC stock of the year 2000 (Schillaci et al., 2017) amounted to 37.44 t ha^{-1} and its range predicted at a R^2=0.47. Similar or lower fit statistics were found when other similar algorithms were applied in many other countries including humid, tropical, monsoon, and drylands (France, Indiana, Western Ghats – India, Nigeria) (Akpa et al., 2016; Martin et al., 2014; Mishra et al., 2009; Seen et al., 2010). The estimation procedure individuated annual average rainfall and temperature as fundamental factors of SOC accumulation and depletion, respectively. The importance of temperature on increasing SOC stock was found to be high only when soil water availability is adequate to sustain the microbial activity (Ma et al., 2014). In general, the higher was the clay content of soil, the higher its SOC stock. This results agrees with studies showing the strong SOC protection ability of clays (e.g. Six and Paustian, 2014) and others also found clay content an important feature on SOC stock estimate (Martin et al., 2014). This suggest that measure to mitigate soil C loss (through reduced erosion rates or augmented C input) strongly need to deal with the texture information. This can also give important information to estimate the rate of SOC variation in time, especially when climate change scenarios are hypothesized. However, the trade-off of the role of SOC on climate change and effects of climate change on SOC at a given location, ecosystem or area depends on various management and environmental variables (e.g. soil texture or tillage, Stockmann et al., 2013). In this framework, the study period in this study, despite selected according to the highest availability of data per year, allowed us to depict a short-term variation of SOC within a well-characterized period: its beginning (1993) luckily fell soon before a number of European and worldwide policy measures which profoundly impacted agriculture, including the Regulation EEC 1272/88 on set-aside; the United Nations Framework Convention on Climate Change of 1993; and the World Trade Organization Marrakesh Agreement. Its end (2008) fell soon after the abolishment of the compulsory set aside in the EU and the decoupled CAP EU payments to agriculture in 2005. This makes it a period of low agricultural dynamic in term of land use change and management techniques, the latter of which were dominated by deep ploughing. In particular, we found that only the area covered by CCP increased by 55%, which was likely due to the temporarily conversion of grassland to pastures or land abandonment. As expected, we found that the SOC of ARA was lower than the SOC of VFO and those of VFO lower than CCP. In general, we found that SOC increased from 1993 to 2008 in the island. We mostly attribute it to the application of Good Agricultural and Environmental Conditions and recourse to the set aside, and ease of increase SOC in low-SOC soils (Borrelli et al., 2016; Kämpf et al., 2016), such as those in the present study. In the northern, rainy, part of Sicily, in spite of conditions conducive to SOC accumulation, we found a reduction of SOC and this was strongly related to soil erosion potential. Similarly, a fifth of the increase of SOC in the ARA and VFO areas was explained by catchment area, landforms, valley depth and channel network base level, which are related to soil deposition

Conclusions

Space-time mapping of SOC can be a valuable tool to aid in the study of the global carbon cycles at wide scale and guide decision-making processes. Here we showed that such processes also relies on existence or accessibility of data, including SOC at representative locations, bulk density, land use, soil texture, rainfall, temperature and RS data. The results of the present experiment also yield valuable information for assessing the effect of a climate change scenario on SOC stocks and their spatial distribution. Finally, the present results can imply both agronomic and policy consequences at the district level and call for an intervention on soil fertility to maintain agriculture productivity (Acutis et al., 2014; Dono et al., 2016). These results can help in calibrating models of SOC dynamic under various management or climate change scenarios.

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