Sub-chapter 3.5.3

Soil carbon as an indicator of Mediterranean soil quality

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Two forms of carbon in Mediterranean soils

Soils are considered as one of the largest C pools on Earth, after the oceanic and geologic reservoirs. The soil C pool comprises two distinct components: soil organic carbon (SOC) and soil inorganic carbon (SIC), which roughly contribute 2/3 and 1/3, respectively (Batjes, 1996).

Soil organic carbon (SOC) represents about 50% of soil organic matter, by consequence "soil organic matter" and "soil organic carbon" are often confused and used interchangeably. Soil organic matter corresponds to all organic materials in soil, i.e. any material produced originally by living organisms (plant, animal, microorganisms) at various stages of decomposition. Soil organic matter is a

Table 1
Estimated dryland carbon stocks

	Biotic (Gt)	Soil		Total (Gt)	Ratio (%)
		Organic (Gt)	Inorganic (Gt)		
Hyperarid and arid	17	113	732	862	28
Semiarid and dry subhumid	66	318	184	568	18
Dryland total	**83**	**431**	**916**	**1 430**	**46**
Global total	**576**	**1 583**	**946**	**3 104**	
Global total ratio (%)	14	27	97		

Source: Millennium Ecosystem Assessment, 2005 (dryland chapter)

continuum of simple and complex molecules. It constitutes a dynamic soil carbon pool, regularly fed by organic residues and in interaction with the mineral particles of the soil. Soil organic matter influences soil functions and properties. It has a key/role in the overall behaviour of soils and agroecosystems, as it provides energy for soil microorganisms, nutrient storage and supply (nitrogen, phosphorus and potassium) for plant production, improves soil structure and is thus involved in the ability of soil to hold water and resist erosion. Maintaining organic carbon in soil is equivalent to maintaining the soil organic matter and a part of the soil fertility. By consequence soil organic carbon content is often considered to be the prime soil quality indicator, with respect to its agricultural and environmental functions.

Soil inorganic carbon (SIC) represents different C forms involved in a solid-solution-gas phase equilibrium, as carbonate minerals (mainly $CaCO_3$), as aqueous carbonic dioxide, bicarbonate HCO_3^- and carbonate CO_3^{2-} ions in soil solution, and as a gas carbonic dioxide CO_2. In humid regions, SIC tends to get dissolved and fluxes into the groundwater or precipitates deep in the soil or geologic system, whereas in dry regions it precipitates at relatively shallow depths as a result of sparse rainfall and insufficient leaching (Gocke et al. 2011). Because of this, about 90% of the global SIC pool is found in arid and semiarid regions (Eswaran et al. 2000), such as the Mediterranean region. Despite agreement about its large size as a carbon pool (950 Gt), little attention has been paid to the dynamic of the SIC pool, which is considered to be very slow and less influenced by anthropogenic disturbance than the SOC pool. However, there is increasing evidence that the solid-solution-gas phase equilibrium in the SIC system may be shifted in one way or another (to CO_2 emissions or $CaCO_3$ precipitation) by external factors such as management practices, e.g. cropping and irrigation, and human-led environmental changes.

The dynamics of the SIC pool could be impacted by land management. Indeed, irrigation to enhance crop production in the Mediterranean region is often practiced with groundwater laden with dissolved calcium bicarbonate (Ca^{2+} and HCO_3^-). When used for irrigation, this water promotes calcium precipitation in the form of calcium carbonate and could modify the equilibrium between the different forms of inorganic carbon in soil. The addition of plant residues enhances biological activities (root and microorganism respiration) resulting in an increase in CO_2 partial pressure, which may either lead to an enhanced trapping of CO_2 through carbonate precipitation, or to a decrease in soil pH resulting in the dissolution of carbonates. There are very few studies that try to understand and explain the contradiction between the results of the impact of soil management on SIC dynamics (Monger et al. 2015). More research is needed on that specific issue.

How soil organic carbon benefits soil fertility and the environment

In semi-arid regions, improving water management while avoiding loss of soil organic matter, and thus maintaining the soil organic carbon pool, is essential to preserve soil against degradation and ensure food security for societies. Combating soil desertification requires effective organic matter and water management in order to maintain a sufficient level of fertility for sustainable production. Thus, the techniques for water and soil conservation management are also recognized as effective soil organic carbon management techniques. Water conservation and fertile sediment retention enhances soil fertility and facilitates the growth of natural or replanted vegetation around the structures as half-moon or stone bunds.

Soil carbon is linked to soil organic matter, as 50% of soil organic matter is soil organic carbon. Soil organic matter ensures a part of soil fertility as it allows for storage of nutriments for plant growth, stimulates soil biodiversity and contributes to soil structure stability. Maintaining the soil organic matter pool is essential in sustainable land management and soil productivity (fig 1).

Besides soil fertility, soil organic matter is also seen as the biggest C reservoir of terrestrial ecosystems after carbon fossil stock (see fig 2). Storing C in soil is seen as a means to mitigate atmospheric CO_2 concentration and Green House Gas emissions (GHG emissions, fig. 1). Thus C balance from soil to the atmosphere is a local issue for soil conservation, agricultural production and food security and at the same time a global issue to limit climatic change. Soil carbon is recognized as an indicator of soil quality in terms of its agricultural and environmental functions.

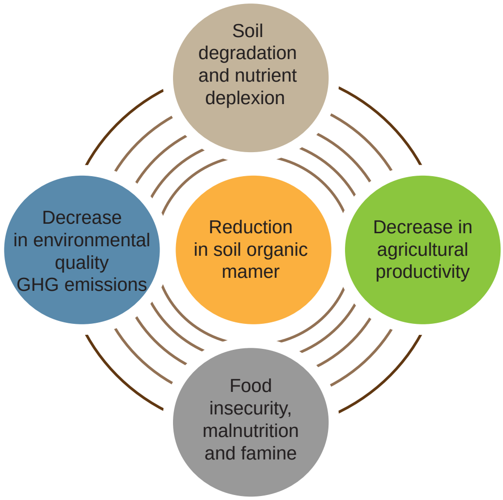

Figure 1
The vicious circle between the decrease in soil organic pools, land degradation and food insecurity (from Lal, 2004 : Soil carbon sequestration impacts on global climate change and food security. Nature 304(5677): 1623-1627).

Measuring or evaluating SOC after changes in management practices

Most Mediterranean soils exhibit low (≤2%) or very low (≤1%) SOC content especially in the southern side of the Mediterranean sea, with a mean SOC content of about 1.1% in the top 0-30 cm for the North Africa region and national means of SOC ranging from 0.67 to 0.79% for Morocco, Tunisia, Algeria and Egypt (Henry et al. 2009). Limited SOC content in the Mediterranean soils is mainly the result of a limited net primary productivity. These low C inputs driven by limited soil moisture availability could be exacerbated by crop residue competition for livestock feeding or the introduction of long fallowing in the crop rotation. Besides low C inputs to the soil, some agricultural management, such as intensive deep-tillage (e.g. moldboard ploughing) may also boost SOC losses. Deep-tillage enhances microbial activity by homogenization of soil moisture and oxygenation and incorporation of crop residues into deep soil, and thus speeds up soil organic matter mineralization and loss. Farming practices that enhance carbon storage are needed for sustainable land management, soil productivity and protection of the environment.

Many soil and management techniques have long been known to maintain or enhance the soil organic matter content: use of compost, manure, cropping residues to "feed" the soil: soil cover techniques, grassed strip, trees, or any

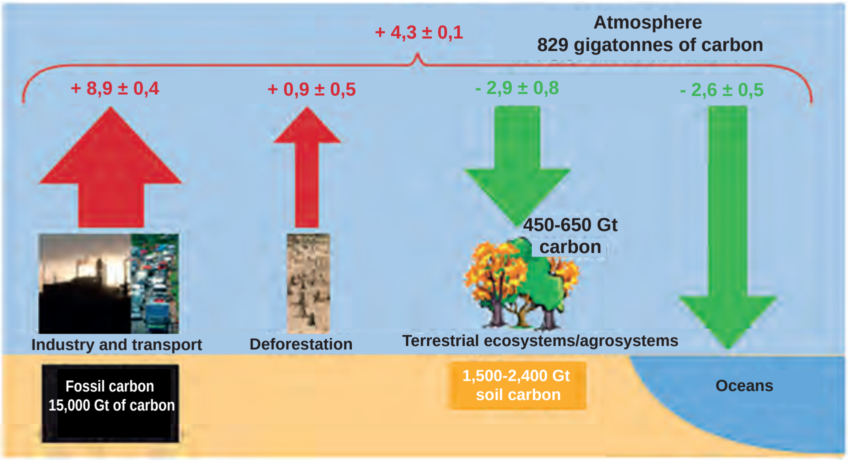

Figure 2
Human activity CO_2 emissions against C stocks, expressed in Gt C or in billions of tonnes of C, and fluxes, expressed in Gt C yr^{-1}, between ecosystems and atmosphere (mean values for 2004-2013, Le Quéré et al. 2014, Earth Syst. Sci. Data Discuss., 6, 1–90, 2014).

land management that preserves soil from erosion, improves water infiltration and enhances soil fertility. To evaluate the efficiency of these techniques to restore, maintain or enhance the soil organic carbon stock, scientists and stakeholders need to quantify soil carbon stocks.

Countries should regularly provide national inventories of greenhouse gas emissions and potential sinks of C for the agriculture and forestry sectors. This comprises national estimates of soil organic carbon (C) stocks (Box 1). These inventories require quantifying the soil carbon stocks on large territories where variability can be large. The development of new measurement techniques for C stock monitoring, that are faster and cheaper than classical techniques are needed (e.g. infrared-spectrometry). Models are also being developed to predict the impact of agriculture and forestry changes on C balances at large scale (region to country) (Box 2).

Carbon stock within the soil profile: the importance of deep carbon

Most of soil carbon surveys focused on the first 30 centimeters of soil (0-30 cm). However, if measured only on the topsoil (0-30 cm), SOC stocks are not representative of the real stock of C stored in the soil, especially in the deep soils of the alluvial cultivated plains. The total carbon stock could be underestimated from 30 to 65 % in Tunisia (Box 1) or on a toposequence in North Algeria (Bounouara et al. 2016) or up to 80% in Cardinael et al. 2015 (Box 3).

Box 1
A specific study "national soil carbon stocks, a case study in Tunisia"

Assessment of carbon contents and carbon stocks in Mediterranean soils is often difficult. The first difficulty is encountered during the sampling process, due to the presence of stones in the soils. In addition to the low organic carbon content and its heterogeneous distribution, sampling representative samples could be hard. The second difficulty concerns the analysis. Most soil carbon measuring methods estimate the total soil carbon content (organic and inorganic carbon). The soil sample must be decarbonated when the analysis is focused only on organic carbon. This decarbonation procedure is difficult and expensive.

In addition, estimation of soil C stocks requires soil bulk density values to convert C content (g C kg^{-1} soil) to a mass of C per unit area (tC ha^{-1}). However, because it is labour-intensive, costly and tedious especially in rocky soil with a high coarse-element content, direct measurement of bulk density is often lacking for soils in arid and semi-arid conditions. Using a pedotransfert equation is an easy option to predict soil bulk density using data from soil surveys, e.g. soil texture or data easier to measure in the field. These predictive functions are specific to regional conditions and need to be built especially for the Mediterranean context (Brahim et al. 2012).

Estimation of national SOC stocks could be conducted after predictive functions using different databases, e.g. soil maps or soil types. Globally the different estimations of SOC stocks for large areas gave similar results and identified the same regions with high SOC stocks. However, the local SOC variability was not precise enough and depends on the predictive function use (Brahim et al. 11). Brahim et al. (2011) organized a soil database with 238 soil profiles corresponding to 707 soil horizons. The mean and median SOC contents of top-soil were 1.17% and 0.86% respectively. The spatial variation of SOC contents are mainly explained by the climatic zones and the soil texture. The global SOC stocks in Tunisian soils are about 0.42-0.46 PgC (0-30 cm) and 1.03-1.13 PgC (0-1m) (Brahim et al. 2011).

Box 2
EX-Ante Carbon blance Tool (EX-ACT)

Ex-Act is a tool developed by FAO in collaboration with IRD to perform ex-ante estimates of the impact of agriculture and forestry development projects on GHG emissions and carbon sequestration in soil and biomass. This tool is especially useful to evaluate the carbon impact of agricultural policies such as land use change incitation (i.e. deforestation, forestation, forest degradation, annual/perennial crops, irrigated rice, grasslands, livestock, inputs, energy, or other investments such as road or warehouse construction). Estimation of C balance is based on IPCC default values (Tier 1), region specific coefficients (Tier 2) are therefore needed to get more accurate C balance results.

Box 3
A specific study "Agroforestry in South of France"

Agroforestry is a land use type where trees are associated with crops or pastures within the same field. In Southern France, a sub-humid Mediterranean region, a study evaluated the potential of organic carbon storage in soil and biomass under an 18 year-old agroforestry system with hybrid walnut trees at 110 trees ha^{-1} + durum wheat. The accumulation rates were 0.35 t C ha^{-1} yr^{-1} in the first meter of soil, and 0.75 tC ha^{-1} yr^{-1} in the above-ground tree biomass. The stored soil organic carbon was mostly coarse organic plant residues (particulate organic matter) which may be rather labile SOC fractions. This study demonstrated the potential of alley cropping systems to store SOC under Mediterranean conditions, but suggested that the additional SOC is vulnerable to any future land use change (Cardinael et al. 2015).

Different types of land uses or soil managements affect the stocks, dynamics and forms of SOC in topsoils but their effect on deep C is still unclear. Because SOC is considered to be less dynamic in subsoils than in topsoils, SOC in subsoils were not studied a lot. However, the SOC in deep soil can contribute to SOC stocks and also be a potential source of CO_2. Indeed, some studies in Mediterranean regions showed that SOM could have high C and N mineralization rates even in subsoil. This surprising result was attributed to specific pedoclimatic constraints under Mediterranean soils (Rovira and Vallejo, 1997, 2002). Therefore, SOM characterization and dynamics in deep soil horizons under the Mediterranean pedoclimate was still unclear because of few available data. Its distribution in the landscape and its forms must be characterized in order to understand its dynamics.

The vulnerability of soil carbon

Terrestrial ecosystems play a major role in regulating atmospheric CO_2 concentrations, as the net balance of photosynthesis and respiration corresponds to a current terrestrial sink of about 2.6 Gt C yr^{-1}. Soil respiration, including autotrophic respiration by roots and heterotrophic respiration by microorganisms, has been estimated to be approximately 100 GtC yr^{-1} (IPCC, 2007) with the half being produced by heterotrophic respiration. Thus it is essential to estimate and predict the impact of soil management and climate change on the microbial activities involved in SOC decomposition to predict the vulnerability or sensitivity of SOC stocks to climate change, *i.e.* increasing temperature, dry-wet cycles, and extreme events. Particular attention is currently paid to the effect of climate changes on Mediterranean region, where increased temperature, decreased and more concentrated rainfall, and an increased frequency of extreme events are forecast.

Understanding soil carbon dynamics is especially critical in semi-arid regions, such as North-West Tunisia, where SOC stocks are low and agricultural productivity is already limited by climatic conditions. A study for North West Tunisian soils indicated a moderate and positive response of soil respiration to temperature; Q_{10} of soil respiration was evaluated to 1.7 (Hamdi et al. 2011). Q_{10} is the proportional change in respiration with a 10 °C increase in temperature. This value of Q_{10} was in the current Q_{10} range values given in the literature, 2.6±1.2 (Hamdi et al. 2013). It seems that these Mediterranean soils have no specific behavior when temperature increases. However, maintaining soil at high temperature up to 40°C for one month, which could be possible in Tunisian semi-arid topsoils, decreases microbial biomass and substrate availability and consequently affects the temperature sensitivity of soil respiration.

In addition, it is not yet clear how and under what conditions the large inorganic carbon pool of Mediterranean soils may be affected by changing climatic conditions. Studies of the positive or negative effects of irrigation or rain events on the contribution of carbonates to the CO_2 emissions from dryland soils are conflicting (Emmerich, 2003; Serrano-Ortiz et al. 2010). In addition, no study has considered the impact of soil temperature on CO_2 emission from calcareous soils in drylands soil, where heat waves are expected to become more frequent and extreme within the 21st Century (IPCC, 2007). A better understanding of SIC dynamics and their role in ongoing global change is particularly critical for arid and semiarid areas, where SIC is the most important C form. In addition, certain methodological issues persist which add uncertainty to the investigation of CO_2 fluxes from calcareous soils to the atmosphere (Chevallier et al. 2016).

Conclusion

As the soil carbon content varies on multiannual scales, other indicators which are more sensitive to the soil organic status can be used for earlier detection of change trends. These indicators involve enzymes, microbial biomass or soil organism biodiversity. They are more sensitive to soil functioning changes but also more complicated to obtain and to use. Soil organic carbon content is thus recognized as one of the main indicators to monitor soil quality, for its agricultural and environmental functions by many national and international institutions, initiatives and partnerships (see sub-chapter 3.5.4). As soil C dynamics is poorly studied in Mediterranean context, more research is needed in order to evaluate the content and quality of soil carbon in relation to the quality of Mediterranean soils.

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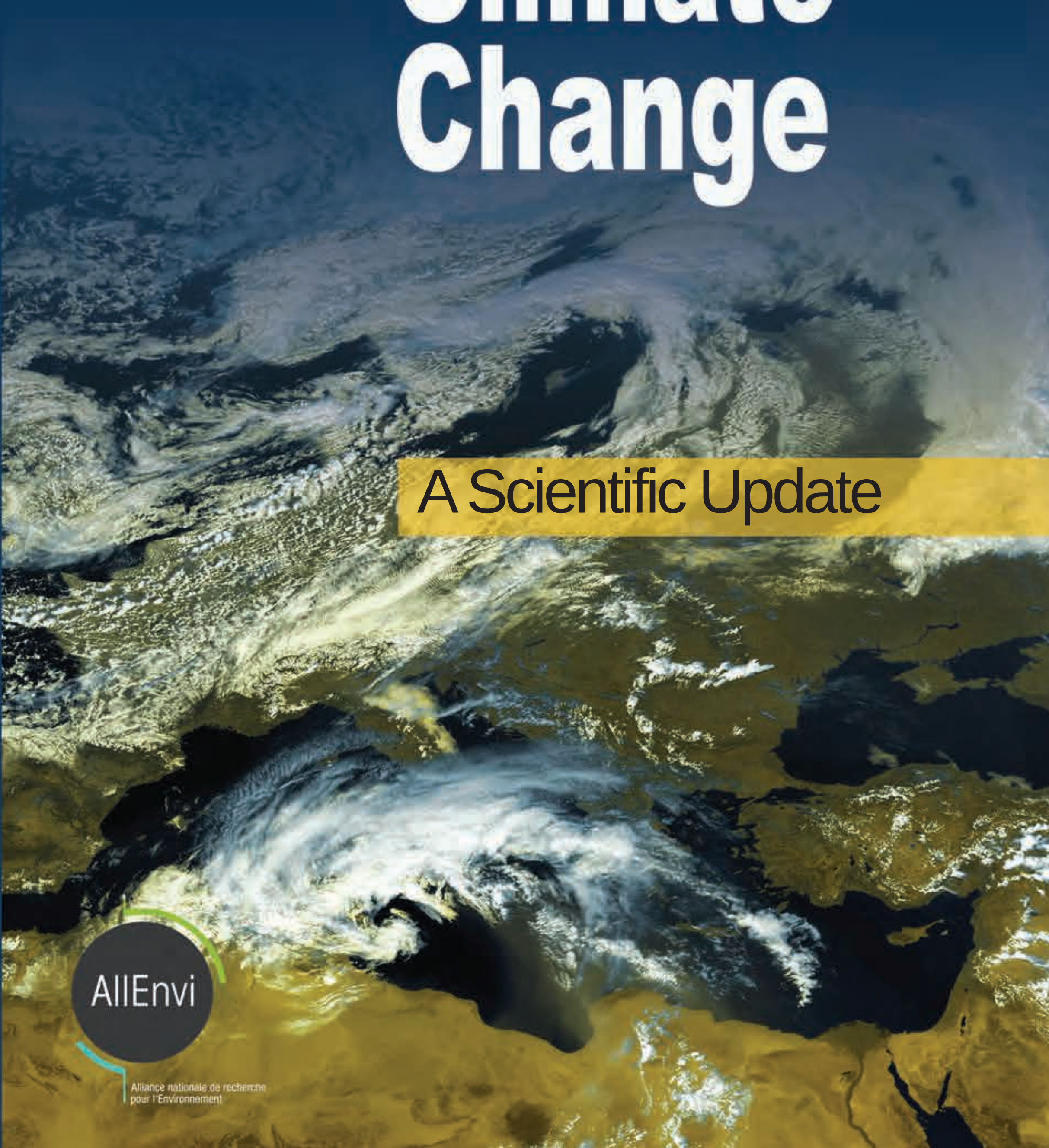
The Mediterranean Region under Climate Change

A Scientific Update



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A Scientific Update

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