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# Managing Mediterranean soil resources under global change: expected trends and mitigation strategies

Philippe Lagacherie<sup>1</sup> · Jorge Álvaro-Fuentes<sup>2</sup> · Mohamed Annabi<sup>3</sup> · Martial Bernoux<sup>4</sup> · Sami Bouarfa<sup>5</sup> · Abdelkader Douaoui<sup>6</sup> · Olivier Grünberger<sup>7</sup> · Ali Hammani<sup>8</sup> · Luca Montanarella<sup>9</sup> · Rachid Mrabet<sup>10</sup> · Mohammed Sabir<sup>11</sup> · Damien Raclot<sup>1,8</sup>

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**Abstract** The soils of the Mediterranean Basin are the products of soil processes that have been governed by a unique convergence of highly differentiated natural and anthropogenic drivers. These soils are expected to be dramatically affected by future climate and societal changes. These changes imply that suitable adaptive management strategies for these resources cannot simply be transposed from experiments that are performed in other regions of the world. Following a framework that considers the chain of “drivers-soil process-soil capital-ecosystem services/disservices,” the paper reviews the research undertaken in the Mediterranean area on three

types of Mediterranean soil degradation than can be expected under global change: (i) soil losses due to the increase of drought and torrential rainfall; (ii) soil salinization due to the increase of droughts, irrigation, and sea level; and (iii) soil carbon stock depletion with the increase of temperature and droughts. The possible strategies for mitigating each of these degradations have been largely addressed and are still studied in current research projects. They should include changes in agricultural practices, soil water management, and vegetal material. As a pre-requisite for the site-specific adaptations of such mitigation strategies within viable Mediterranean

✉ Philippe Lagacherie  
philippe.lagacherie@inra.fr

Jorge Álvaro-Fuentes  
jorgeaf@eead.csic.es

Mohamed Annabi  
mannabi@gmail.com

Martial Bernoux  
martial.bernoux@ird.fr

Sami Bouarfa  
sami.bouarfa@irstea.fr

Abdelkader Douaoui  
aekdouaoui@gmail.com

Olivier Grünberger  
olivier.grunberger@ird.fr

Ali Hammani  
ali.hammani@gmail.com

Luca Montanarella  
luca.montanarella@jrc.ec.europa.eu

Rachid Mrabet  
rachidmrabet@gmail.com

Mohammed Sabir  
miloudsaadia@hotmail.com

Damien Raclot  
damien.raclot@ird.fr

<sup>1</sup> INRA, UMR LISAH, Montpellier, France

<sup>2</sup> CSIC, Zaragoza, Spain

<sup>3</sup> INRAT, Tunis, Tunisia

<sup>4</sup> IRD, UMR Eco&Sol, Montpellier, France

<sup>5</sup> IRSTEA, UMR G-EAU, Montpellier, France

<sup>6</sup> Université de Khemis Miliana, Khemis Miliana, Algeria

<sup>7</sup> IRD, UMR LISAH, Montpellier, France

<sup>8</sup> IAV Hassan II, Rabat, Morocco

<sup>9</sup> European Commission, DG JRC, Ispra, Italy

<sup>10</sup> INRA, Rabat, Morocco

<sup>11</sup> ENFI, Sale, Morocco

agrosystems, it is highlighted that methodological advances are necessary in integrated assessment of agricultural systems and in finer resolution soil mapping.

**Keywords** Soil · Erosion · Carbon · Salinization · Climate change

## Introduction

The Mediterranean Basin is the land region surrounding the Mediterranean Sea that has a Mediterranean climate, with mild, rainy winters and hot, dry summers. It is the largest of the world's five Mediterranean climate regions (2,085,292 km<sup>2</sup>). It stretches west to east from Portugal to Syria and north to south from northern Italy to Morocco and surrounds the Mediterranean Sea, including parts of Spain, France, the Balkan states, Greece, Turkey, Syria, Lebanon, Israel, Palestine Authority, Jordan, Egypt, Libya, Tunisia, and Algeria as well as 5000 islands that are scattered around the Mediterranean Sea.

Along with its water, coastlines, and biodiversity, soils constitute one of the Mediterranean Basin's vulnerable natural resources. Their productivity enhancement and the care given to their conservation and management have been a big contributor to the spread of successive past civilizations. By contrast, their degradation has been a cause of crisis and constant decline in the past and has inflicted a high cost on most of its countries (Croitorou and Sarraf 2010). Even today, soil degradation in its various forms constitutes a significant threat to the future of the Mediterranean Basin (De Franchis and Ibanez 2003; Lahmar and Ruellan 2007).

The Mediterranean Basin hosts a unique combination of soil-forming factors, climate conditions, parent material, and reliefs (Yaalon 1997; Ryan et al. 2006; Zdruli 2014). Furthermore, Mediterranean soils have been heavily impacted, if not built, by the most ancient agriculture in the world (De Franchis and Ibanez 2003). This impact makes the Mediterranean soils and soil patterns very different from other regions of the world.

The Mediterranean Basin is also a global change hotspot. Most general circulation models forecast drastic changes in temperatures and rainfall regimes for this area (Dubrovský et al. 2013). Some of these changes have been observed recently (Lionello et al. 2014). In addition, increasing population and market pressures have induced important land use changes (Sluiter and Jong 2006; García-Ruiz and Lana-Renault 2011) that could become even greater in the future (IPCC 2014).

Both the Mediterranean's soil peculiarities and its strong regional dynamic relations with global change imply that suitable adaptive managing strategies for Mediterranean soil resources cannot be simply transposed from experiments that were performed in other regions of the world. Instead,

research should be performed on strategies that specifically address Mediterranean soil conditions.

In this paper, a multidisciplinary group of soil scientists reviews the current research on managing Mediterranean soil resources through a common framework (Dominati et al. 2010), highlighting the primary challenges that should be faced to conserve the ability of these resources to provide their expected services.

## Specificities of Mediterranean soil resources

The soils of the Mediterranean region are products of soil processes that have been governed by a unique convergence of highly differentiated natural drivers (climate, relief, and parent material) and strong historic human activity. These drivers have provided some remarkable characteristics to the Mediterranean soil cover that are highlighted in the following section. We use in the following the World Reference Base for Soil Resources terminology and classification system (IUSS Working Group WRB 2006).

### Shallow soils

Leptosol, and Regosol, covers a large part of the Mediterranean region (European Soil Bureau Network 2005; Zdruli et al. 2011; Jones et al. 2013). These characteristics reflect the natural predominance of erosion processes, which are enhanced by the conjunction of (i) a marked relief in which 45% of the areas have slopes greater than 8% because of active tectonics at the contact of the African and Eurasian plates (De Franchis and Ibanez 2003), (ii) the high frequency of very intense rainfall events ( $> 100 \text{ mm h}^{-1}$ ) during the autumn and winter seasons, and (iii) lesser protection by vegetation against erosion because of the severe summer droughts, burning, overgrazing, and deforestation that reduce the vegetation coverage (García-Ruiz et al. 2013). The evolution towards shallow soils is often counterbalanced by human practices such as terracing in hilly areas (Tarolli et al. 2014). Conversely, farming is known to greatly accelerate the erosion rates relative to soil production (Amundson et al. 2015), particularly when cultivated fields replaced the natural vegetation that was originally dominated by Mediterranean scrublands and forests. Finally, shallow and skeletal soils in Mediterranean landscapes are often closely associated with Cambisols—young-aged soils—that have formed on the downhill colluvium of eroded material and represent large areas in this region too.

### Soil carbon contents

Mediterranean soils have not been consciously managed to store or sequester carbon. Hence, most of these soils exhibit low to very low soil organic carbon (SOC) contents. This

information is particularly well documented for the European countries in the Mediterranean Basin (European Soil Bureau Network 2005; Zdruli et al. 2004). For countries along the southern side of the Mediterranean Sea, Henry et al. (2009) calculated a mean SOC content of 1.1% in the top 0–30 cm for the North Africa region, with mean national SOC values ranging from 0.67 to 0.79% for Morocco, Tunisia, Algeria, and Egypt. National-scale studies have confirmed those values, e.g., for Tunisia, Brahim et al. (2012) organized a soil database with 238 soil profiles corresponding to 707 soil horizons. The authors reported that the mean and median SOC contents of the topsoils (depth < 40 cm, 249 horizons) were 1.17 and 0.86%, respectively.

Limited SOC content is the result of several biotic and abiotic processes and factors, with climate and management being the two most influential factors in the Mediterranean region. Rainfall shortage limits the net primary productivity, and, in turn, soil C buildup. Low C inputs driven by limited soil moisture availability are exacerbated by the adoption of certain management practices. Crop residue competition for livestock feeding and the introduction of long fallowing in the crop rotation are two examples of typical management practices in the Mediterranean region that have contributed to the reduction of C inputs that are returned to the soil. In addition to decreases in C inputs, agricultural management may also boost SOC losses. In the Mediterranean region, the use of intensive deep tillage implements (e.g., moldboard plowing) has been a common practice for centuries. Inversion tillage generates favorable soil conditions for microbial activity (i.e., it homogenizes the moisture content along the soil profile, favors soil oxygenation, and incorporates crop residues into the soil), thus accelerating soil organic matter mineralization and loss.

Another important consideration is that those soils usually contain an important amount of inorganic carbon, most of which is present as carbonates as a result of the dissolution of calcareous parent material by winter rainfalls and precipitation during dry summer periods (Yaalon 1997). This composition results in soils with calcareous material accumulations in their profiles (Calcisols, Kastanozem), which are more frequent in the Mediterranean Basin than everywhere else in the world (Ryan et al. 2006). However, there have been few investigations concerning the short-term pattern of inorganic C stocks because of complex interactions and balances between atmospheric C and organic and inorganic forms of soil C (Bernoux and Chevallier 2014).

### Irrigation and salinity

The Mediterranean Basin is also characterized by a large surface of irrigated soils, usually in the flat areas. In the Near East/North Africa countries, the irrigated area is estimated by the FAO to be 31 million ha (2012). This figure does not

take the north side of the Mediterranean into account. The International Commission of Irrigation and Drainage estimates a lower area of 25 mha for all Mediterranean countries that are equipped with irrigation systems (ICID 2014). This difference is likely linked to informal (and private) groundwater irrigation and small-scale irrigation systems.

Irrigated soils are prone to secondary salinization (or human-induced salinization) related to imbalances in the soil salt budget. Human-induced salinization is as old as irrigation. Salinization forced the early settlers of Mesopotamia, the Indus river basin, and China to abandon their land (Ghassemi et al. 1995). More than 50 years ago, modern states promoted the development of irrigation, primarily for orchards and fruit production. The primary model of irrigation development was based on large irrigation schemes using water stored in large and medium dams. These systems generally faced water management problems (water supply-demand coordination issues and inefficient water transport and field application), leading to a rise in groundwater levels and to the so-called twin menace of “waterlogging and salinity” (Bouarfa and Kuper 2012). Despite this well-known challenge, there is still no accurate estimation of how the corresponding soils were affected by secondary salinization in irrigated areas. Paranychanakis and Chartzoulakis (2005) estimated that salinization in the Mediterranean Basin is a serious problem with some 16 million ha out of 74 million ha of today irrigated lands, under the assumption that the ratio of 25% of salt-affected soils of irrigated area soils in 1974 put forward by Szabolcs (1989) is still valid in spite of progresses in irrigation techniques. For example, salinization occurs in most Moroccan irrigated systems. The available data on salinity indicates that approximately 500,000 ha that are located primarily in the command areas are threatened by salinity (Dahan et al. 2012).

### Spatial soil patterns

Apart from the above-evoked characteristics, Mediterranean soil cover is also remarkable for the occurrence of extremely complex soil patterns with large short-scale and anisotropic variations caused by the rapid successions of contrasting parent materials, erosion, and re-deposition of soil material within short distances and the long-term impacts of human practices. Many detailed studies across this region have revealed such complex patterns (e.g., Pardini et al. 2004; Gomez et al. 2012; ...).

It is worth noting that the existing soil data in the Mediterranean area are available at a spatial resolution that is much too coarse for mapping such complex patterns. The most recent review on the data available for Mediterranean soils was compiled by the European Commission (Yigini et al. 2013). It updates the previous assessment that was completed within the Soil Atlas of Europe (European Soil Bureau

Network 2005). A large amount of additional information was collected by the EU-funded project MedCoastLand (Zdruli et al. 2007). The harmonization of national soil surveys allowed for the production of the European Soil Database (EUSIS) at 1:1,000,000, further extending among other countries to those of the southern part of the Mediterranean Basin. Few Mediterranean countries have developed their own national database at a larger scale than 1:1,000,000. Some 1:250,000-scale soil databases are available in Italy, Albania (Zdruli 2005), Lebanon (Darwish 2013), and Mediterranean France (Bomand et al. 1994). Larger scale soil maps cover the entire or at least substantial portions of Mediterranean countries. Israel (Crouvi et al. 2013), southern Portugal (Goncalves et al. 1999), and the coastal part of Albania (Zdruli 2005) are covered by a 1:50,000 soil map. Complete coverage at 1:25,000 and 1:100,000 exists for Bulgaria and Turkey, respectively. Badraoui and Stitou (2001) have developed a comprehensive report on the availability of soil information and maps in Morocco. Finally, there have been many local surveys in most countries at various scales that are hard to locate and describe, with the notable exception of Tunisia, for which a database of scanned soil survey reports (BEST) has been developed (Derouiche 2011, pers. communication).

### Analyzing the future of Mediterranean soil resources under global change

The latest global change model projections (Dubrovský et al. 2013) have indicated the presence of clear climate change in the Mediterranean area. The results show an increase in temperature during all seasons and for all parts of the Mediterranean with good inter-model agreement. The precipitation is projected, with a lower degree of model agreement, to decrease in all parts and all seasons (most significantly during the summer), except for the northernmost parts in winter. Furthermore, increased mean daily precipitation sums on wet days are expected for some seasons, and some parts of the Mediterranean, which may imply higher daily precipitation extremes. A decreased probability of wet day occurrence will imply longer drought spells all across the Mediterranean. All these projections converge towards an even more aggressive climate that may highly impact Mediterranean soils.

In addition, the demographic projections indicate a less-than-expected but still clear increase in the population of the Mediterranean area with a total population of 500 million inhabitants in 2010 that is expected to reach 563 million inhabitants by 2025 (Carella and Parant 2014). This increase will primarily concern urban and coastal areas, and the population of rural areas will remain stable. This change will lead to reconfigurations of national spaces into a mosaic of mushroom cities and rural areas (ARP Parme 2011).

The two above-evoked trends will work together to substantially increase the pressure on Mediterranean soil resources, i.e., producing more on less arable lands that have been depleted by urbanization.

In the following section, the future of Mediterranean soil resources is examined by considering the expected impacts of the trends evoked above and by exploring the most promising levers that humans can use to counterbalance the negative impacts. For that reason, we followed the holistic soil assessment approach proposed by Dominati et al. (2010) by considering the chains of “drivers soil process-soil capital-ecosystem services/disservices.” The central concept is soil capital, which is defined as the stocks of natural and human-added assets in soils that yield a flow of valuable ecosystem goods or services. This soil capital can be described through a list of measurable soil properties (e.g., soil carbon stocks or available water capacity). The soil capital is included in a broader chain that considers (i) the upstream processes governing the soil capital formation, maintenance, and degradation and their associated natural and human drivers and (ii) the downstream soil ecosystem services, with beneficial flows arising from soil capital stocks and fulfilling human needs and disservices and adverse changes in soil capital leading to a loss of ecosystem services. The processes are themselves impacted by a set of drivers among which one can distinguish the actual observable trends and the mitigation strategies that could alleviate and even delete the impacts of trends.

We chose to select three challenging issues that deserve attention to address the future of these Mediterranean resources. Our analyses are summarized in Figs. 1, 2, and 3. The scientific background supporting these figures and the related research proposals are developed hereafter.

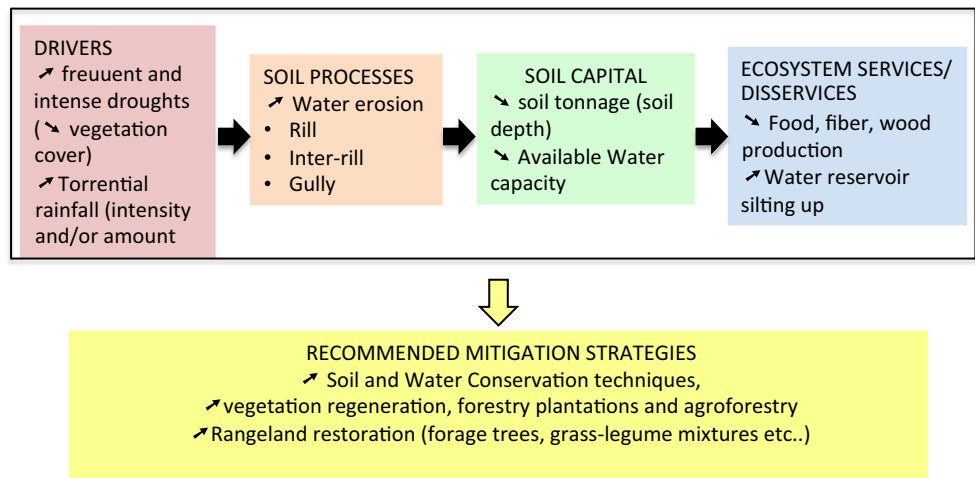
### Mitigating soil losses

According to the trend scenario, climate change is expected to increase water erosion processes, which will in turn diminish the tonnage of available soil (Fig. 1). This loss of soil depth has direct and obvious on-site effects relating to agricultural production including losses of plant nutrients, soil water reserves, and alterations in soil properties (Lal 1998). It also has an off-site effect related to water reservoir siltation. In fact, reservoir siltation represents a major issue for water resource management strategies in the Mediterranean Basin, especially in North African and eastern Mediterranean countries (Ayadi et al. 2010). Higher sediment yields (SYs) were reported in this environment than the yields for many other regions across the world (Woodward 1995; Vanmaercke et al. 2011).

In the Mediterranean area, and especially in European Mediterranean countries, the sheet and rill erosion rates that are measured at the plot scale are generally lower than the sediment yields (Cerdan et al. 2010; Vanmaercke et al. 2012). This finding was explained by the large fraction of rock



**Fig. 1** Expected evolution of soil capital as driven by water erosion processes that are caused by global change trends, and possible mitigation strategies



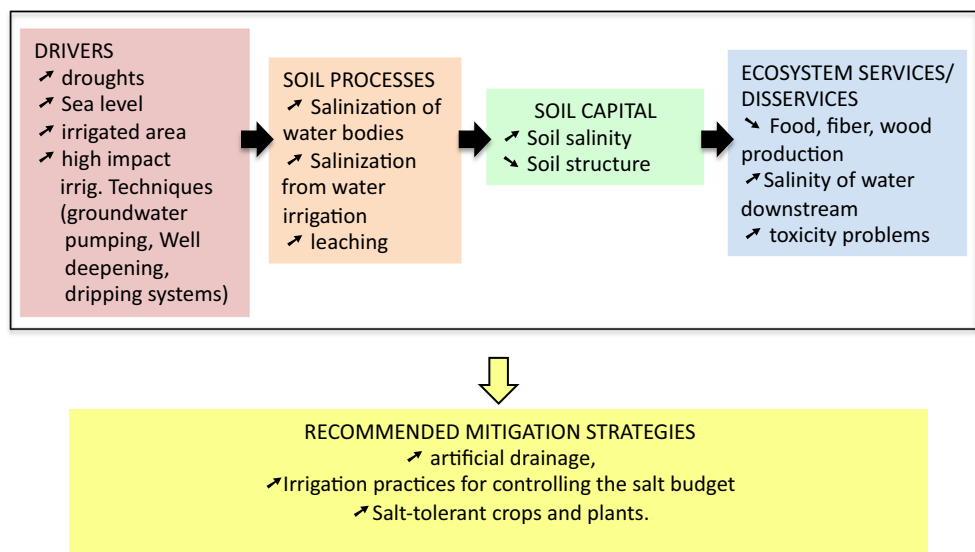
fragments at the topsoil and by the importance of erosion processes that are not active at the plot scale, such as gully erosion, landslides, and riverbank erosion. More generally, gullies and especially badlands were often identified as the primary sources of sediment responsible for reservoir siltation in Mediterranean environments (Heusch 1970; De Vente et al. 2006, 2008; Poesen et al. 2003; Simmoneaux et al. 2015), even if a recent fingerprinting study showed that gully erosion was the predominant sediment source for only two of five small Tunisian catchments (Ben Slimane et al. 2015). It is noteworthy that water erosion is considered the most active process that induces soil losses (Govers et al. 2014), which explains why tillage or wind erosion effects are less frequently measured in the Mediterranean context.

The expected effect of climate change is twofold. First, by increasing the intensity of the largest events, an increase in the rainfall intensities or amounts will likely increase water erosion. In this specific Mediterranean context, González-Hidalgo et al. (2007) showed the high dependence of soil

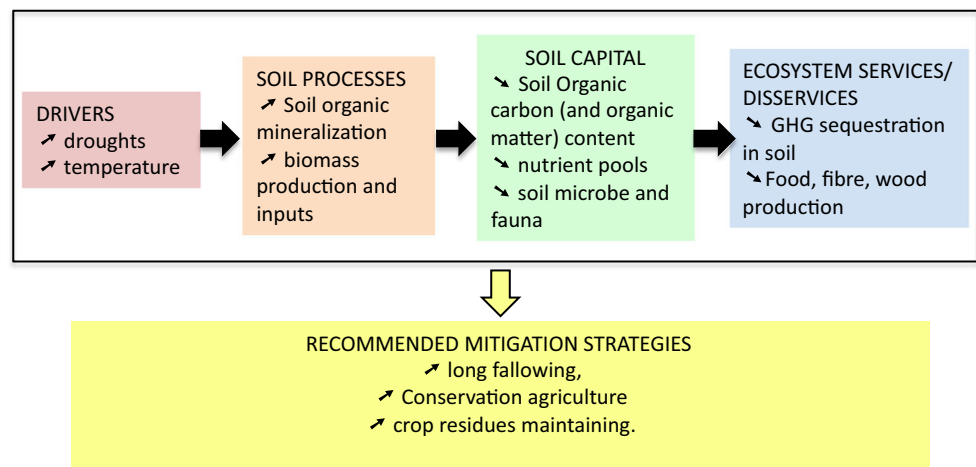
erosion with the most intense rainfall events because the three highest daily erosive events represented more than 50% of the annual eroded soil. Second, increasing droughts may induce decreased vegetation cover, which will have negative effects on soil losses and silting up because vegetation cover is one of the key factors in erosion control (Wischmeier 1975; Morgan 2005).

However, mitigation strategies for counterbalancing this negative trend are possible. Mediterranean civilizations successively developed or improved a large range of Soil and Water Conservation (SWC) techniques to improve water conservation and management, increase agriculture production, and reduce soil erosion (Fig. 1). These techniques are primarily based on slope correction/water velocity reduction (i.e., bench terraces), increasing the ground cover (i.e., cover crop, mulching, permanent cover using tree/crop associations), and/or soil quality improvement (i.e., amendments). Recently, SWC has been broadened towards sustainable land management or conservation agriculture, fostering less soil

**Fig. 2** Expected evolution of soil capital as driven by secondary soil salinization processes from global change trends, and possible mitigation strategies



**Fig. 3** Expected evolution of soil capital as driven by carbon storage processes caused by global change trends, and possible mitigation strategies



disturbance, the retention of crop residue, and continuous ground cover, which have been shown to decrease erosion in comparison with conventional agriculture based on deep tillage (Mrabet et al. 2012). The efficiency of conservation agriculture at improving soil water storage is well recognized in the Mediterranean Basin (Mrabet 2011; Moreno et al. 2010; Ben Moussa-Machraoui et al. 2010). Studies that were conducted on inter-row crops such as olive groves (Francia Martínez et al. 2006; Gómez et al. 2009) or vineyards (Paoissien et al. 2015) also supported the recommendation for non-inter-row tillage and for maintaining a high inter-row vegetation cover with a cover crop or grass cover. However, all these techniques have been introduced so far with varying degrees of success, depending on the environmental and societal contexts (García-Ruiz et al. 2013; De Graaff et al. 2013). Maintaining a continuous land cover may for instance have positive impacts on soil protection and negative impacts on production because of water competition in the semi-arid context (Marques et al. 2010).

The primary scientific issues that are used to help define adaptation strategies for the Mediterranean area are summarized below. First, there is a need to better understand the spatiotemporal variability of Mediterranean catchment erosion behavior in terms of sediment sources, active erosion processes, and transport efficiency from sediment sources to downstream reservoirs. Promising recent methodological developments are based on the use of fingerprinting techniques or the repetitive acquisition of fine digital elevation models that enable diachronic analysis. European or Mediterranean networking initiatives by scientists and long-term erosion-monitored catchments such as the R\_Osmed network (<https://sites.google.com/site/rosmedsicmed/home/introduction>) or COST initiative ([http://www.cost.eu/COST\\_Actions/essem/ES1306](http://www.cost.eu/COST_Actions/essem/ES1306)) will also help us better understand this variability in relation to the specific role of major/extreme events in catchment sediment yields or in the role of sedimentological connectivity.

A second set of research actions must be dedicated to studies of the past of the Mediterranean Basin through a review of the large range of adaptation techniques used in this region and a comparison of their evaluations in terms of soil protection efficiency and acceptability by the farmers as it will be investigated in the forthcoming MASCC (Mediterranean Agricultural Soils Conservation under global Change) project. The implementation of these adaptation techniques within spatially explicit numerical models devoted to the Mediterranean environment is also a requirement that can help managers to plan the type, number, and location of adaptation techniques to implement within a catchment or a watershed for present and future conditions (Gumiere et al. 2014).

The last set of necessary actions consists in improving our knowledge of future conditions to anticipate efficient adaptation techniques. Because of the stormy nature of major events in the Mediterranean context, we still need to improve the predictions of subdaily rainfall characteristic predictions as hourly rainfall intensities. Feedback between climate change and land use change is also critical for adaptation strategy planning, especially in the Mediterranean context, where vegetation cover is a major lever for soil protection.

### Avoiding secondary salinization

According to the trend scenario, increasing drought and sea-level rise and the spread of irrigation in combination with changes in irrigation techniques are expected to reinforce salinization processes and to deplete soil leaching, which will in turn increase the Na and Cl contents of soils and degrade soil structures (Fig. 2). Crop production will be affected when the salinity exceeds the threshold values that depend on each crop's sensitivity during critical stages. Most of the plants suffer yield or biomass production decreases when the soil salinity exceeds  $4 \text{ ds m}^{-1}$ , which represents the limit for defining soils with salinity issues. Osmotic stress is the primary process that is involved with effects similar to drought and

freezing; plants face difficulties when extracting water from the root zone. Secondary effects are brought on by toxicity from Na and Cl and from deficiencies of other elements such as Ca, K, and Zn. All the functions and cycles of a plant can be affected. Another effect comes from the exposure of saline soil to changes in the primary ion on the adsorbed phase to  $\text{Na}^+$ . Afterwards, if the salinity decreases, for instance in the case of remediation, then clay may disperse, ruining the soil structure, hampering drainage, and triggering reduction. In landscapes, each upstream area delivers a water supply to downstream ecosystems, and this flow is considered an essential “ecoservice.” When salinity increases in the soil of inland fields, leaching may provide salinity to downstream and neighboring systems through runoff, drainage, or underground contamination, fuelling the extension of salinity problems at the landscape scale.

In the near future, rising sea levels will increase the salinity pressure on coastal soils and aquifers, but the primary effect is expected from the increase in droughts in Mediterranean countries, which will accentuate irrigation needs. This increase may even be reinforced by the expected needs of agricultural intensifications (see the introduction of this section). For the time being, only a few trials have been performed to simulate increased soil salinity ahead of climatic scenarios in irrigated lands. Preliminary results were obtained by modeling the fate of salinity in southern Alicante (Spain), which is cultivated for citrus and legumes. Climate change is creating an enlargement trend in the soil surface that is affected by salinity, from 19 to 34%. Investigators indicate that this effect could be mitigated by a 20% increase in the present irrigation rate. It is feared that salinization issues in the region will reinforce the direct effect of climate change.

Furthermore, this trend will be significantly reinforced by the recent evolution of irrigated agriculture techniques. First, groundwater has become increasingly important for irrigation. At present, of the 300 million ha of irrigated land in the world, some 110 million now depend on groundwater, which represents 25% of the total irrigation water (Siebert et al. 2010). The Mediterranean countries are no exception. In North African countries, groundwater has been responsible for the redesign of irrigation frontiers, and it covers over 60% of the total irrigated area, supplying more than 500,000 farms with irrigation water (Kuper et al. 2016). After being perceived as a threat, groundwater gradually became a cherished resource. Salinity issues and solutions also changed in nature because they are not linked to waterlogging problems but are primarily related to the water quality of groundwater. In particular, the depletion of inland groundwater has led farmers to pump from deeper and older geological layers, which are sometimes affected by a natural geological salinity, and in coastal plains, the salinization of aquifers occurs through sea intrusion, threatening some of the most productive irrigated soils.

Second, the water-saving policies used in several Mediterranean countries largely depend on the generalization of drip irrigation technologies instead of traditional surface irrigation techniques. As a result, the area in Mediterranean countries under drip irrigation has significantly increased in recent years. For example, according to the Moroccan ministry of agriculture (Bennouniche 2014), the area equipped with drip irrigation has increased from less than 100,000 ha in 2000 to 360,000 ha in 2013. The aim of this modernization is to “save water” by increasing the irrigation efficiency according to the phrase “more crop per drop.” However, it is important to note that drip technique benefits related to efficiency will increase with the water volume and can be used at the expense of the proper soil leaching fraction that is required to remove excess salts.

The secondary salinization process is partially linked to natural conditions but is also under the control of farmer practices at the field level and water management at the irrigation scheme level, which offers opportunities to undertake mitigation strategies for counterbalancing the above-evoked soil degradation (Fig. 2). Secondary salinization depends on the salt budget at the field level as related to farmer irrigation practices, and the leaching processes that they implement depend on farmer perceptions of the problem (Bouarfa et al. 2009). Salinization is also linked to water management and artificial drainage facilities at a larger scale to avoid waterlogging and the salinization of soils by capillary rise (Alexandratos and Bruinsma 2012).

It is thus important to re-engage in research to address secondary salinity issues in a renewable fashion. At present, research efforts in the Mediterranean Basin are mostly dedicated to employing effective Integrative Water Resources Management (IWRM) at regional scales (100 km<sup>2</sup> or more), and they mostly consider water volume aspects. Water salinity constraints are often neglected during modeling, which indicates the difficulty in assessing the complexity generated by the behavior of a particular soil interface under the influence of the individual agricultural practices of irrigation and amendment. The salinity of soil and water should therefore be quantified as a primary constraint to effective IWRM, and it should be considered important for resource volume conservation objectives. In this sense, more research is needed to test the resilience and acceptability of agrosystems with low irrigation rates as general soil salinity problems increase.

Another issue is that scientific studies are often solicited for situations in which severe salinity problems have already been identified by the farmers (e.g., obvious soil salinity crusting and/or dramatic yield decreases). Therefore, because most past studies focused on severe salinization situations, they are likely to present rough representations of the processes that may be inadequate for modeling large timescales with good accuracy. Therefore, the research should focus on ways to identify discrete evidence of early salinization that would



allow for underthreshold management and/or accurate modeling of the long-term soil fate with respect to salinity.

### Maintaining soil carbon stocks

According to the trend scenario, climate change may further diminish the soil organic carbon content of the Mediterranean area (Fig. 3). As SOC is also the primary constituent of soil organic matter (SOM), representing approximately 50% of its weight (Pribyl 2010). Thus, SOC is also often an indicator of soil fertility in environmental services. The loss of SOM and therefore of SOC especially when initial levels are low, as in dryland regions, results in the degradation of soils and their associated agronomic and environmental functions and services (Lal 2004). Figure 3 represents global reported tendencies encountered in the literature; however, it should be highlighted that some models and studies predict increasing SOC under certain management practices and predicted climate change conditions, as in Alvaro-Fuentes et al. (2012). Moreover, mineralization depends not only on temperature but also on moisture regime, and whereas the behavior of the temperature driver is well established towards an increase, it is less consensual concerning the precipitation regime both in quantity and in distribution annually. Therefore, uncertainties are still high as illustrated in the example below.

Few studies have addressed the impact of future climate change in Mediterranean regions. Hamdi et al. (2011) designed a study to examine an agricultural soil from northern Tunisia (i) to investigate the effects of temperature variations of up to 50 °C on soil respiration and (ii) to test the effect of further organic carbon additions. The results do not support an important increase in soil respiration sensitivity to temperatures ranging from 20 to 40 °C. Only at 50 °C, such as during a heat wave, was there a significant increase in the water-soluble carbon, which was likely related to either dead microbial cells or SOC solubilization. Overall, the results indicate a moderate response in the soil respiration to high temperatures, as shown by the  $Q_{10}$  value that was close to 1.7, even from 40 to 50 °C, illustrating the need to be cautious when using a mechanistic model such as Roth C based on a  $Q_{10}$  higher than 2. Indeed, a review analysis by Hamdi et al. (2013) collected and calculated  $Q_{10}$  values from incubations of 253 unique soils from 63 published studies. The authors encountered a large variability of observed temperature sensitivities of SOC dynamics, with a mean value of 2.04, but with a standard deviation of 1.09 and a median of 1.85. Moreover, the authors showed that this variability is still largely unexplained.

Another important aspect of CC is related to water availability. The drying and wetting of Mediterranean soils was shown to stimulate SOM decomposition and carbon dioxide emission. This effect is known as the “Birch effect” (Birch 1958). Yemadje et al. (2016) recently employed a Soudano-Sahelian context that was in some ways comparable to

Mediterranean climate conditions (annual rainfall from 900 to 950 mm, but with a long dry period). Soil wetting and mulching were shown to increase soil carbon mineralization, but frequent wetting-drying cycles did not increase the total soil C mineralization (Yemadje et al. 2017). But, these last authors also reported that conflicting results for the effect of wetting-drying cycles on C and N mineralization can be found in the literature, with higher or lower, or similar values for C and N mineralization in soils subjected to wetting-drying cycles.

In terms of adaptation strategies in combination with the need to fight agricultural soil degradation and organic C depletion, several approaches were proposed and tested in a Mediterranean context, and some of them were widely adopted by stakeholders at the plot or watershed level.

The change of land use in a semi-arid area is a strategy in which the major patterns are related to the reduction in long-term fallowing (Peterson and Westfall 2004). Annual soil cultivation that employs appropriate nutrient management increases the soil C return (root, stubble,...) because the above and belowground biomass production was increased in comparison with that of the fallow system. The choice of crop species and cultivars is an important key to maximizing the production of crop residues, which are a major resource for organic inputs in Mediterranean croplands. In the cereal-livestock system, straw is largely exported out of the plot instead of being incorporated back into the soil. In addition, stubble is intensively grazed primarily to the south of the Mediterranean Sea (Ryan et al. 2006). The implementation of crop rotations with plants that allocate more carbon to top and subsoil through a deep root system is an adaptation measure for sinking C. The improvement of rangeland productivity by legume sowing, shrub plantation, and integrated livestock are widely used strategies to boost the soil fertility in the arid part of the Mediterranean region.

Field studies that were undertaken in Morocco and Tunisia by Mrabet et al. (2001) and Jemai et al. (2012) showed 14 and 28% increases in the SOC from the 0 to 20-cm soil layer after 11 and 7 years of switching from conventional tillage to conservation agriculture practices, respectively. In Spain, Alvaro-Fuentes et al. (2012) observed a 23% SOC increase in the top 30-cm layer of soil after it was converted to conservation agriculture for 13 years. More generally, the concentrations of organic matter in topsoils of Mediterranean regions were found to increase routinely under no-tillage systems because of the favorable shift in the accumulation and decomposition balance (Kassam et al. 2012; Friedrich et al. 2014).

However, the wide adoption of conservation agriculture among farmers in the Mediterranean regions is still limited. According to Kassam et al. (2012), the total Mediterranean cultivated land under conservation agriculture is 1.53 million ha.

Research questions are still focused on refining the expected level of C sequestration attained in the different bioclimatic zones, and also by considering the deeper soil layers from which C losses have been registered under other climatic conditions. However, one of the most important points concerns the adoption and mainstreaming of conservation agriculture, which will have a strong impact on the management of the residues at the landscape and even subnational level. Residues are also an important source of biomass resources that are made available for livestock. Synergies (other services in the fight against erosion) and trade-offs (biomass competition should then be addressed as well) to find the most appropriate technical solutions for farmers and smallholders whose objectives are yield and income increase.

By contrast, the concentrations of organic matter in topsoils from Mediterranean regions routinely increase under no-tillage systems because of the favorable shift in the balance of accumulation and decomposition (Kassam et al. 2012; Friedrich et al. 2014).

### **Challenging transversal issues for the future of Mediterranean soil resources**

Apart from the above-evoked ongoing research on each driver-process-soil capital-ecosystem service chain upon separation, the management of soil resources under global change raises some transversal issues that are detailed here.

#### **Towards a reliable change in soil management practices within viable agrosystems**

Many of the mitigation strategies evoked in the next sections are based on deep changes in agricultural practices. Beyond the successful results obtained on experimental farms, the massive introduction of such strategies within actual Mediterranean agrosystems is still a challenge. For example, the broad adoption of conservation agriculture among farmers in the Mediterranean region is still limited because of possible negative impacts such as the decrease in grazing resources for livestock through the introduction of mulching, or water stress on agricultural production from the introduction of a permanent vegetation cover. Another aspect is the need for local and national policies that should support actions for, e.g., building up and raising the status of SOC using the adapted programs and mechanisms with national-wide agricultural strategies such as those within the framework of NAMA. It is now recognized that policies that support sustainable land management practices are focused on both maintaining (preventing loss) and increasing (storing even more) soil organic carbon production for far greater economic, social, and environmental impact than the absolute amount of sequestered carbon (Banwart et al. 2014).

The introduction of mitigation strategies should be applied in a wider context that considers the whole agrosystem explicitly and its socioeconomic environment. An integrated assessment of agricultural systems is therefore required (Van Ittersum et al. 2008).

#### **Towards site-specific adaptations for preserving the soil resource**

Beyond the field and farm levels, Mc Intyre et al. (2009) recommended that the landscape level be considered and that “new cropping patterns adapted to site-specific conditions” be introduced. This approach accounts for the diversity of local contexts (see the first issue in this section) and to admit that “the search for universal truths about causes and remedies for desertification and the appropriate actions to be taken are as diverse as the mosaic of landscape itself” (Thomes 2002). This interpretation is particularly relevant in Mediterranean areas where the complexity of soil patterns (see above) involves a significant diversity of soil properties and soil processes, starting from very small areas such as parcels, farm territories, and small watersheds.

Significant advances are expected from employing spatial organizations of land uses and soil management practices. These choices will ensure the optimal exploitation of local soil characteristics while providing the best pooled result in terms of soil cover protection at the scale of resource watersheds or irrigation perimeters in which collective management is possible (10–100 km<sup>2</sup>).

An example of current research that is being performed in the Mediterranean area to address these opportunities is the ALMIRA (Adaptating Landscape Mosaics of rainfed Mediterranean Agrosystems for a sustainable management of crop production, water, and soil resources) project. ALMIRA aims to explore the modulation of landscape mosaics to adapt to the Mediterranean Rainfed Agrosystems to Climate Change. For that purpose, ALMIRA proposes to design, implement, and test a new integrated assessment modeling approach that explicitly (i) includes innovations and actions in prospective scenarios for landscape evolutions and (ii) addresses landscape mosaics and processes of interest from the agricultural field to the resource governance catchment.

#### **Towards a high resolution for mapping Mediterranean soil properties**

A systematic soil survey of the Mediterranean Basin using the most updated technology and scientific knowledge is still lacking for a site-specific adaptation of local mitigation strategies and should be one of the priority actions in the near future. The specifications of this survey may follow those of the new digital soil map of the world as targeted by the GlobalSoilMap project (Sanchez et al. 2009; Arrouays et al.

2014a). This targeted global soil map is expected to provide quantitative estimates of major soil properties with associated uncertainties at the nodes of a  $90 \times 90$  m grid covering the planet and for a set of fixed soil depth intervals ranging from 0 to 2 m. This new soil map is expected to be largely available through free-access web portals. Researchers (Arrouays et al. 2014b) have suggested the rapid production of a first version of the global soil map by applying largely tested digital soil mapping (DSM) techniques (McBratney et al. 2003; Lagacherie et al. 2007) to existing spatial datasets. These datasets include the input of globally available landscape parameters (e.g., DTM, digital maps of land use, and multispectral remote sensing) and legacy soil data (measured soil profiles, soil maps) that are available in existing soil databases. Interest in the above-evoked digital soil mapping approach for producing the new soil map of the world was tested in various parts of the world including Mediterranean areas such as the Cap Bon region in northern Tunisia (Ciampalini et al. 2012) and the Languedoc-Roussillon region in southern France (Vaysse and Lagacherie 2015). In this latter experiment, successful predictions captured more than 50% of the variability in the mapped soil properties and provided realistic estimates of the prediction uncertainty where possible (for the pH and OC in Languedoc-Roussillon). However, the sparseness of the legacy soil data that were available in current soil databases hampered the capture of the short-scale soil variations of soil properties within the complex Mediterranean soil patterns. A priority should be made for the densification of these soil data by (i) increasing the retrieval of legacy-measured soil profiles, (ii) using soil sensing techniques such as Vis-NIR hyperspectral imagery (Lagacherie and Gomez 2014), or (iii) reviving the field collection of soil data following optimized sampling (Brus et al. 2011). These required efforts for collecting soil data will likely not fully remove the uncertainty on the soil property predictions, considering the short scale of variations of Mediterranean soils. However, the expected progresses brought by GlobalSoilMap—i.e., increasing the spatial resolution of soil predictions, providing quantitative estimations, and providing explicit values of expected uncertainty—may greatly help for site-specific decision making.

## Conclusions

The Mediterranean soil resource is a highly specific research object with regard to (i) its remarkable characteristics as caused by a unique combination of natural and anthropogenic soil-forming factors and (ii) the extent of the expected climate and societal changes that are expected to affect this resource in this region of the world.

In this context, the preservation of Mediterranean soil resources encompasses three crucial challenges: mitigating soil losses, avoiding soil salinization, and maintaining carbon

stocks. For each of these challenges, there are specific studies to continue or initiate to try to gain a better understanding of the soil processes driving the trend evolutions in Mediterranean soil resources and the mitigation strategies that should be applied to preserve these resources.

The effective application of these mitigation strategies also implies progress in the integrated assessment of the Mediterranean agrosystems and in the design of site-specific adaptations to global change. A significant contribution of soil scientists to this task will be to provide improved information on fine-scale Mediterranean soil patterns through advanced digital soil mapping techniques.

Finally, this paper has underscored the urgent need to deepen Mediterranean cooperation with regard to soil research and to enrich the exchange and sharing of technologies, resources, experiences, and knowledge.

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