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

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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 review 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 the increase of droughts, irrigation and sea level and iii) soil carbon stocks 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 agro-systems, 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

1. 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^2). 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 five thousand 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 civilisations. 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 (World Bank, 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). 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 (Dubrovsky et al, 2014). 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 (García-Ruiz et al, 1996; Sluiter et De Jong, 2007) 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.

2. 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, cover a large part of the Mediterranean region (European Soil Bureau Network, 2005, Jones A. et al, 2013, Zdruli, 2011). 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 mm/h) 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 (Jones et al., 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 0.67-0.79% 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 top-soils (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 or 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., mouldboard ploughing) has been a common practice for centuries. Inversion tillage generates favourable soil conditions for microbial activity (i.e., it homogenizes the moisture content along the soil profile, favours 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 hectares (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 fifty 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. Paranychianakis 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 areas 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 harmonisation 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 (http://eusoils.jrc.ec.europa.eu/library/data/250000/Italy.htm), Albania (Zdruli, 2005), Lebanon (Darwich, T., 2008) and Mediterranean France (Bornand et al, 1994). Larger-scale soil maps cover 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).

3. Analysing the future of Mediterranean soil resources under global change

The latest Global Change Model projections (Dubrovsky 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 dis-services 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 distinguishes 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 figures 2, 3 and 4. The scientific background supporting these figures and the related research proposals are developed hereafter.

Mitigating soil losses

Insert figure 1 here

According to the trend scenario, climate change is expected to increase water erosion processes, which will in turn diminish the tonnage of available soil (Figure 2). 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 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 (Heush, 1970; De Vente *et al.*, 2006 and 2008; Poesen *et al.*, 2003; Simmoneaux, 2015), even if a recent fingerprinting study showed that gully erosion was the predominant sediment source for only 2 of 5 small Tunisian catchments (Ben Slimane, 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 two-fold. 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 that 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. Secondly, 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 (Figure 2). 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 toward sustainable land management or conservation agriculture, fostering less soil 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 (Paroissien *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, 2013, De Graaf *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 behaviour 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) 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 project (Mediterranean Agricultural Soils Conservation under global Change). 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 (Gumière *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 sub-daily rainfall characteristic predictions as hourly rainfall intensities. Feedback between climate change and land use change are also critical for adaptation strategy planning, especially in the Mediterranean context, where vegetation cover is a major lever for soil protection.

Avoiding secondary salinization

Insert figure 2 here

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 (Figure 3). 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 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, Zn, etc. 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 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 neighbouring 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 (De Paz Bécares et al, 2012) by modelling 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., 2015). 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.

Secondly, 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 (Figure 3). 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 (FAO, 1994).

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^2 or more), and they mostly consider water volume aspects. Water salinity constrains are often neglected during modelling, which indicates the difficulty in assessing the complexity generated by the behaviour 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 modelling large time scales with good accuracy. Therefore, the research should focus on ways to identify discrete evidence of early salinization that would allow for under-threshold management and/or accurate modelling of the long-term soil fate with respect to salinity.

Maintaining Soil Carbon stocks

Insert figure 3 here

According to the trend scenario, climate change may further diminish the soil organic carbon content of the Mediterranean area (Figure 4). 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 4 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 Álvaro-Fuentes et al. (2012). Moreover, mineralization depends not only on temperature but also on moisture regime, and, whereas the behaviour of the temperature driver is well established toward an increase, it is less consensual concerning the precipitation regime both in quantity and 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 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 20-40°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°C-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 900-950 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 (FAO, 2014). 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 0-20 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 top-soils of Mediterranean regions were found to increase routinely under no-tillage systems because of the favourable 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 hectares.

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 sub-national 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 increases.

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

4. 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 programmes 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 socio-economic 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, IAASTD (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” (Thornes, 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^2).
An example of current research that is being performed in the Mediterranean area to address these opportunities is the ALMIRA project (Adaptating Landscape Mosaïcs of rainfed Mediterranean Agrosystems for a sustainable management of crop production, water and soil resources). 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 Modelling 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 m x 90 m grid covering the planet and for a set of fixed soil depth intervals ranging from 0 to 2 metres. 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 et 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 & Gomez, 2013) 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 regards 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 regards to soil research and to enrich the exchange and sharing of technologies, resources, experiences and knowledge.

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thank you for the revision. Our Guest Editor Wolfgang Ludwig now recommends acceptance of the paper and I agree about the scientific content.

Thank you both for acknowledging that the scientific content is OK.

However, you seem to have ignored my advice from the previous decision letter which was "In addition, I suggest to delete the abstract and write a fresh one. Remember that an abstract should not be part of the introduction - it should rather deliver as many of the findings and conclusions as possible."

Indeed, I am quite serious about this. An abstract, and also the title, are the parts of any publication that are read by most people, and their information content is very important. To say that some authors did this or that does not belong into an abstract. So I would like to repeat this request, and also expand it to provide me with a more specific title that precisely speaks to the content of your paper. Note there is also no such thing in English as "Global Changes".

The abstract has been deeply reworked for matching your advice. There is no more direct reference to authors and we provide a more precise description of our finding. The title of the paper was modified too for giving more precise details on the paper.

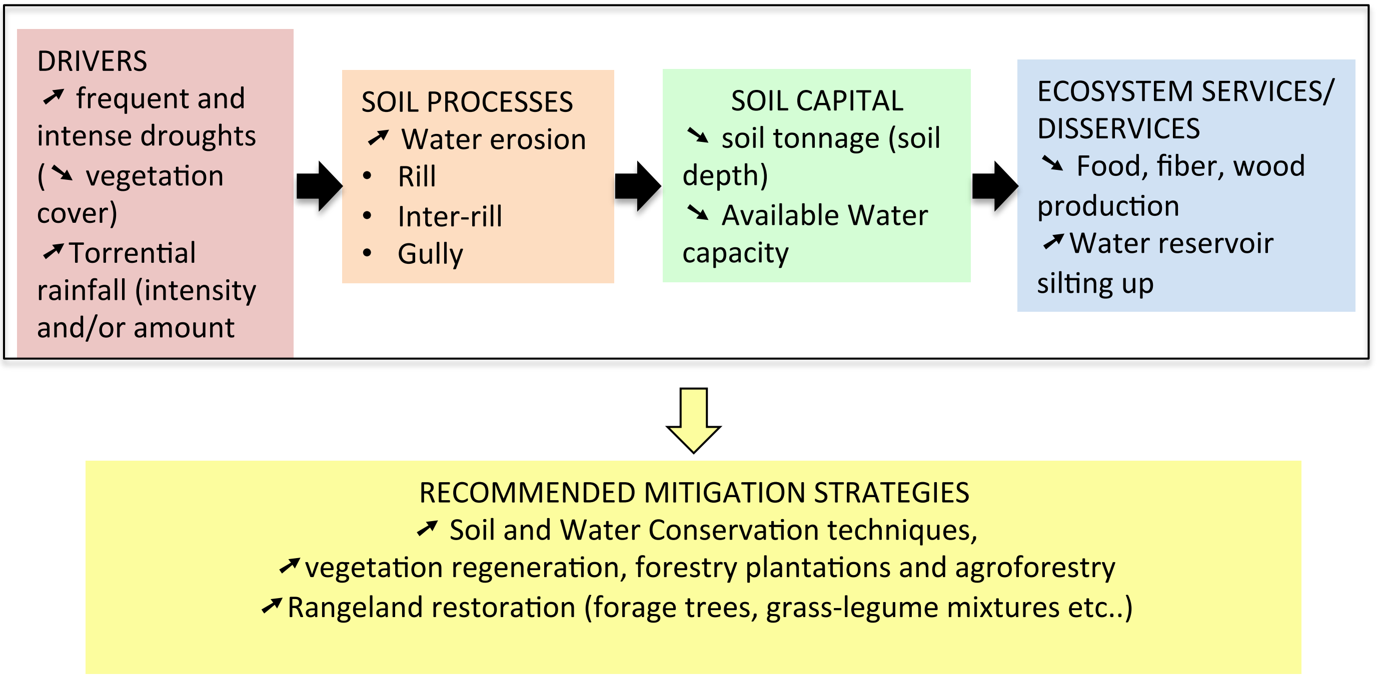
Going through the paper, I also notice that there are minor changes needed: you cannot use "GC" as an acronym, spell out global change if you mean that, but not in plural.
GC were replaced by « global change » and the ‘s’ were deleted

Some references still lack doi-numbers.

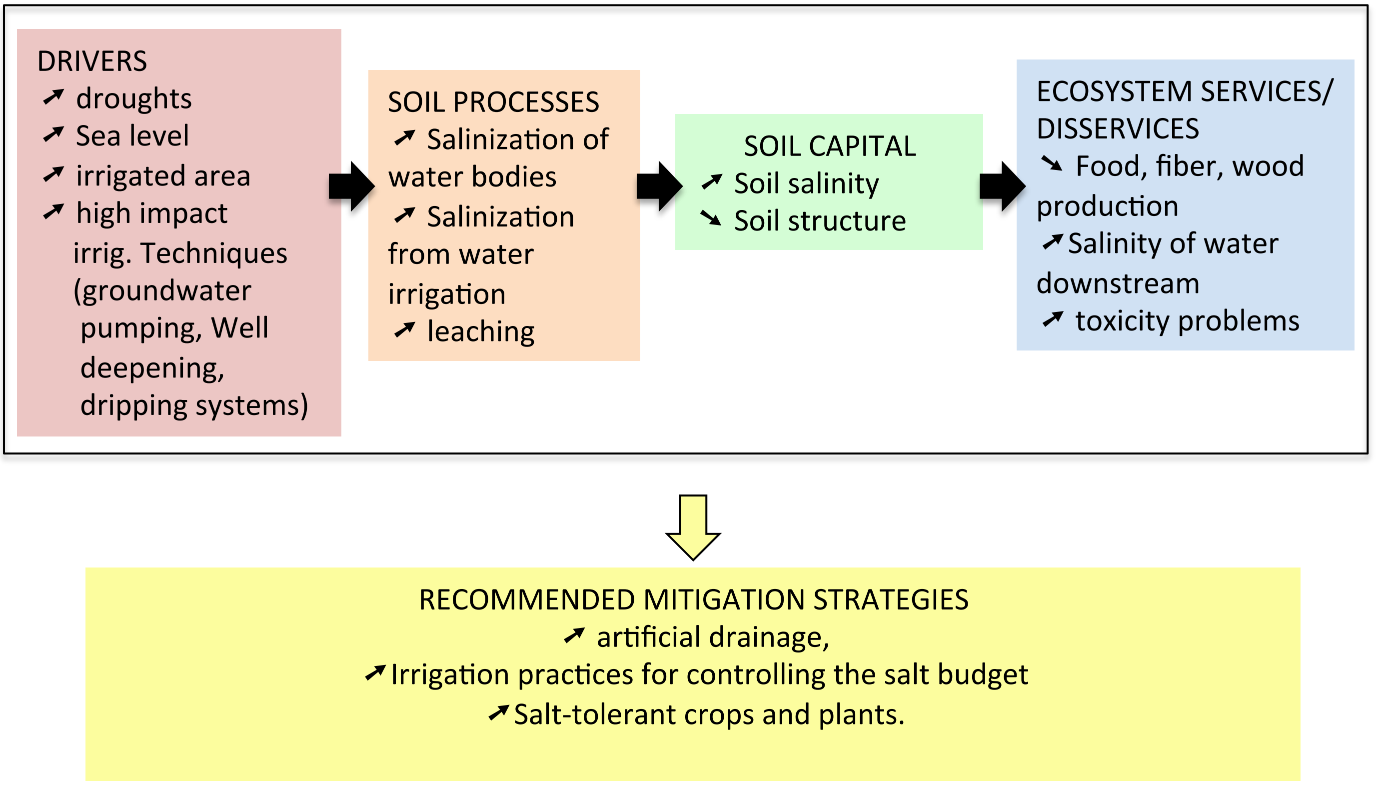
We added 6 more doi to our reference list. 57% of our reference are now documented with a doi. In spite of our efforts, we did not find any doi for the remaining references. Looking at the five most recent REEC papers published as open access papers (on 2017 May18th), we observed that the ratio of documented doi was between 5% and 72% (between 56% and 72% if we only consider « non social science » papers). Our paper match therefore what has been achieved in REEC recent papers.

Finally, I did not earlier pay much attention to the figures. They definitely need to be designed properly. At the moment they are rather tables with some arrows and it is not at all clear to me what they are supposed to represent. Please use an appropriate drawing software to prepare these figures - the publisher has now facilities to offer for doing this in your place.
The figures have been modified for not looking like tables. This allowed to better represent the status of the « mitigation strategies » that have been discussed by the reviewers in earlier versions.

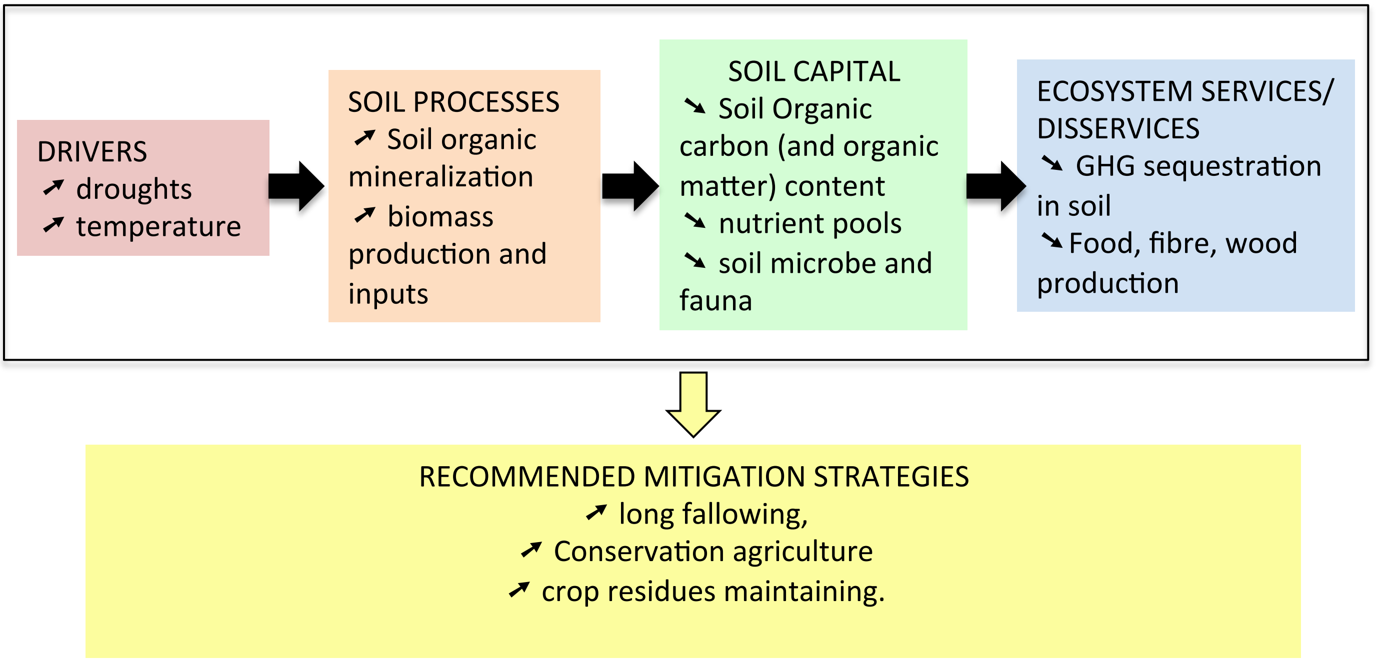
Figure


DRIVERS
↗ frequent and intense droughts (↘ vegetation cover)
↗Torrential rainfall (intensity and/or amount
SOIL PROCESSES
↗ Water erosion
• Rill
• Inter-rill
• Gully
SOIL CAPITAL
↘ soil tonnage (soil depth)
↘ Available Water capacity
ECOSYSTEM SERVICES/ DISSERVICES
↘ Food, fiber, wood production
↗Water reservoir silting up
RECOMMENDED MITIGATION STRATEGIES
↗ Soil and Water Conservation techniques,
↗vegetation regeneration, forestry plantations and agroforestry
↗Rangeland restoration (forage trees, grass-legume mixtures etc..)

Figure


DRIVERS
↗ droughts
↗ Sea level
↗ irrigated area
↗ high impact irrig. Techniques (groundwater pumping, Well deepening, dripping systems)
SOIL PROCESSES
↗ Salinization of water bodies
↗ Salinization from water irrigation
↗ leaching
SOIL CAPITAL
↗ Soil salinity
↘ Soil structure
ECOSYSTEM SERVICES/ DISSERVICES
↘ Food, fiber, wood production
↗ Salinity of water downstream
↗ toxicity problems
RECOMMENDED MITIGATION STRATEGIES
↗ artificial drainage,
↗ Irrigation practices for controlling the salt budget
↗ Salt-tolerant crops and plants.

Figure


DRIVERS
➚ droughts
➚ temperature
SOIL PROCESSES
➚ Soil organic mineralization
➚ biomass production and inputs
SOIL CAPITAL
➘ Soil Organic carbon (and organic matter) content
➘ nutrient pools
➘ soil microbe and fauna
ECOSYSTEM SERVICES/ DISSERVICES
➘ GHG sequestration in soil
➘ Food, fibre, wood production
RECOMMENDED MITIGATION STRATEGIES
➚ long fallowing,
➚ Conservation agriculture
➚ crop residues maintaining.