Challenges of soil carbon sequestration in NENA Region

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Abstract

Near East North Africa (NENA) region spans over 14% of the total surface of the Earth and hosts 10% of its population. Soils of the NENA region are mostly highly vulnerable to degradation, and food security will depend much on sustainable agricultural measures. Weather variability, drought and depleting vegetation are dominant causes of the decline in soil organic carbon (SOC). In this work the status of SOC was studied, using a land capability model and soil mapping. The land capability model showed that most NENA countries (17 out of 20), suffer from low productive lands (>80%). Stocks of SOC were mapped (1:5 Million) in topsoils (0-0.30 m) and subsoils (0.30-1 m). The maps showed that 69% of soil resources present a stock of SOC below the threshold of 30 tons ha^{-1}. The stocks varied between $\approx$ 10 tons ha^{-1} in shrublands and 60 tons ha^{-1} for evergreen forests. Highest stocks were found in forests, irrigated crops, mixed orchards and saline flooded vegetation. The stocks of soil inorganic carbon (SIC) were higher than those of SOC. In subsoils, the SIC ranged between 25 and 450 tons ha^{-1}, against 20 to 45 tons ha^{-1} for SOC. Results highlight the contribution of NENA region to global SOC stock in the topsoil (4.1%). The paper also discusses agricultural practices that are favorable to carbon sequestration such as organic amendment, no till or minimum tillage, crop rotation, and mulching and the constraints caused by geomorphological and climatic conditions. The effects of crop rotations on SOC are related to the amounts of above and belowground biomass produced and retained in the system. Some knowledge gaps exist, especially in aspects related to the impact of climate change and effect of irrigation on SOC, and on SIC at the level of soil profile and soil landscape. Still, major constraints facing soil carbon sequestration are policy relevant and socio-economic in nature, rather than scientific.

Keywords: Drylands, soil organic carbon, soil inorganic carbon, land capability, C stock, conservation practices.

1. Introduction

The Near East North Africa (NENA) region spans over 14% of the total surface of the Earth and hosts 10% of its population (Elhadi, 2005). The largest importer of wheat in the world, this region is also one of the poorer (FAO, 2015). A recent assessment of global hunger index (GHI), based on four indicators -undernourishment, child wasting, child stunting, and child mortality- showed that most of the NENA countries present low to moderate GHI. Countries suffering from armed conflicts, Syria, Iraq and Yemen, are at a serious risk (von Grebmer et al., 2017). With the scarce natural resources and difficult socio-economic conditions, it is questionable whether food security will be reached by

2030, unless a significant change in agricultural practices and governance occurs (FAO, 2017).

Most of the land area of the NENA region falls in the hyper-arid, arid and semi-arid climatic zones. Climate change is expected to exacerbate the scarcity of water, and drought. Weather variability, drought and depleting vegetation are major concerns in the loss of soil productivity and agricultural sustainability. Changes in soil organic carbon (SOC) can affect the emission of greenhouse gases to the atmosphere and negatively influence the global climate (Lal, 2003). In fact, destructive land management practices are impacting soil functions. Land use change, mono-cropping and frequent tillage are considered to cause a rapid loss of SOC (Guo et al., 2016). These agricultural practices disturb the stability of soil characteristics, built under local land cover and climate (Bhogal et al. 2008). Thus, most NENA lands contain ~1 % of SOC, and frequently less than 0.5%.

NENA pedo-climatic conditions present major constraints to carbon sequestration (Atallah et al., 2015). To maintain soil productivity and land quality, several technical and socio-economic measures need to be adopted. Additional efforts oriented to maintaining and increasing SOC can contribute to poverty reduction and achieve food security (Plaza-Bonilla et al., 2015). Good agricultural practices, based on low tillage or no tillage, may result in the reduction of SOC breakdown and the enhancement of the soil carbon pool (Atallah et al., 2012; Cerdá et al., 2012; Boukhoudoud et al., 2016).

In order to compare situations and problems, global soil organic carbon maps are a priority. As recently as December 2017, the GSP-FAO, ITPS launched the version 1 of the global soil organic carbon map, showing the SOC stock in topsoil (http://www.fao.org/3/a-i8195e.pdf). A preliminary assessment of regional SOC stocks, using unified background information, is needed to analyze the challenges facing C sequestration. Mapping the spatial distributions of OC stocks can be used to monitor regional and global C cycles. Accurately quantifying SOC stocks in soils and monitoring their changes are essential to assessing the state of land degradation. At the same time, the predominantly calcareous soils of NENA region are rich in soil inorganic carbon (SIC). The dynamics of SIC and its potential in sequestrating soil carbon are largely unknown and deserves thorough investigation. This paper analyzes the state of SOC and SIC in NENA countries and

outlines challenges and barriers for devising organic carbon sequestration in NENA's impoverished and depleted soils. It also highlights several questions which scientists need to resolve. Finally, it discusses practical agricultural measures to promote SOC sequestration.

Materials and Methods

Data on SOC and soil inorganic carbon (SIC) contents in soils were retrieved from the soil database of the FAO-UNESCO digital soil map of the world (DSMW) at 1:5 Million. Within the database, 1700 geo-referenced soil profiles, collected from all member states of the NENA region, are included (FAO, 2007).

In terms of area, the largest soil units are Yermosols (4670.6 km^2), Lithosols (2914.3 km^2) and Regosols (1193.2 km^2). The great majority of soil classes presents very low to low resistance to erosion and degradation (Table 1). To the contrary, Cambisols, Fluvisols and Regosols are highly resistant to erosion. Soil classes dominated by calcareous rocks (Solonchaks, Rendzinas and Aridisols) have the highest SIC content (Table 1), while Lithosols and Xerosols, subject to regular water and wind erosion, show the smallest SIC.

Table 1. Soil inorganic carbon level and the resistance to land degradation in the major soil units of Near East North Africa region (Source: DSMW, FAO, 2007).

Soil Classes	Area, 1000 km^2	Resistance to Land Degradation	Average SIC content (%)	
			topsoil	subsoil
Cambisols	178.9	High	0.25	0.64
Fluvisols	232.7	High	1.12	1.40
Kastanozems	26.0	High	1.69	3.96
Regosols	1193.2	High	1.18	0.23
Luvisols	121.6	Moderate	0.02	0.11
Phaeozems	3.8	Moderate	0.40	0.70
Rendzinas	25.6	Low	2.80	4.80
Lithosols	2914.3	Low	0.01	0.06
Vertisols	45.4	Low	0.45	0.72
Xerosols	498.5	Low	0.25	0.45
Yermasols (Aridisols)	4670.6	Low	2.50	2.30
Solonchaks	230.1	Very low	3.60	3.90
Solonetz	31.2	Very low	0.06	0.36
Arenosols	384.0	Very low	0.00	0.00

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The SOC content can vary depending on soil type, topography, land cover, erosion-sedimentation and soil management. Within the topsoil (0-0.30 m), the SOC contents are between 0.13% and 1.74%, while in the subsoil (0.30-1 m) values range between 0.16 and 0.9% (Figure 1). Two out of the three predominant soil classes (Xerosols and Aridisols) have SOC contents below 0.5%. Overall, the NENA soils are poor in SOC, as less than 20% of soil resources have SOC contents above 1.0%.

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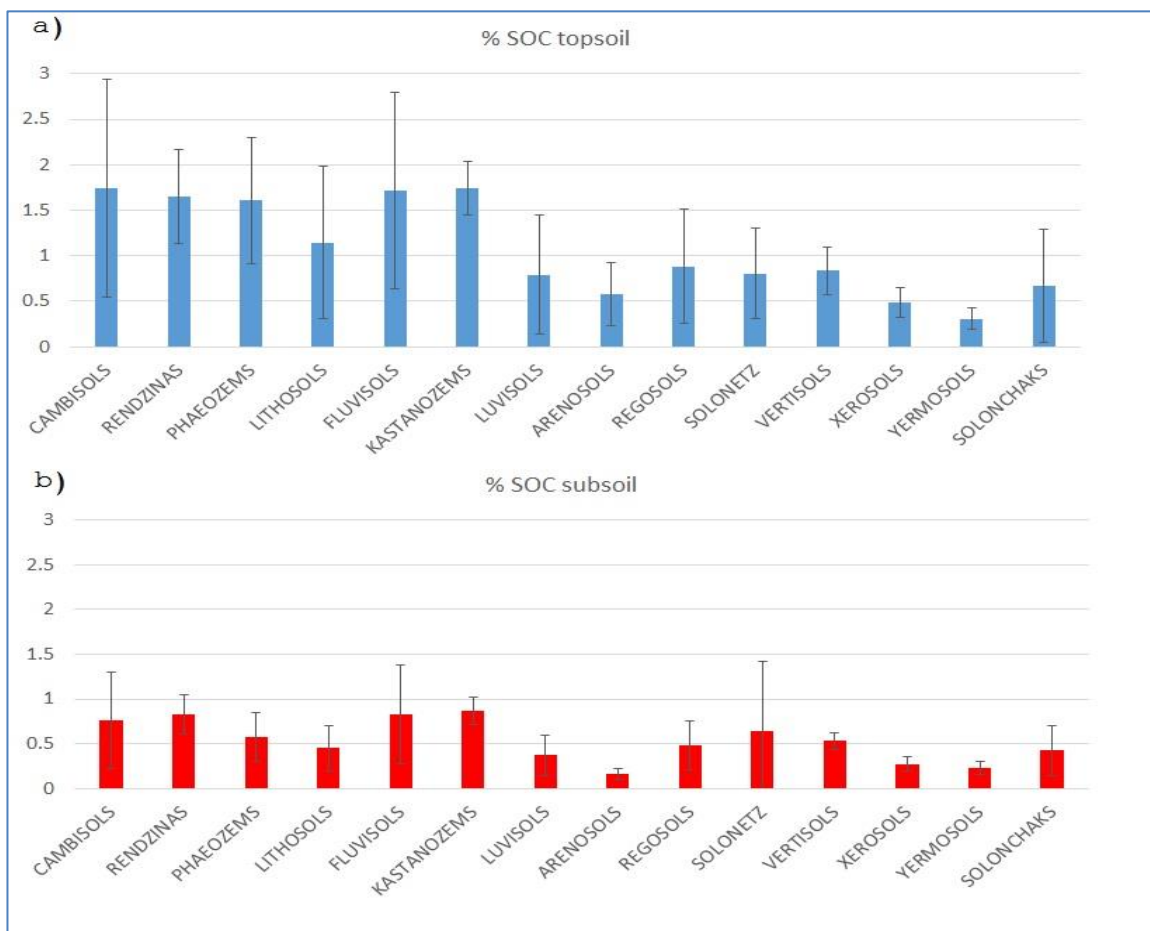
Figure 1. SOC content (%) in topsoil and susbsoil in the major soil groups of NENA region with standard deviation related to soil class.

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The NENA soil map was prepared using the topographic map series of the American Geographical Society of New York, as a base, at a nominal scale of 1:5.000.000. Country boundaries were checked and adjusted using the FAO-UNESCO Soil Map of the World. Soil classification was based on horizon designation, depth, texture, slope, and soil physico-chemical properties. Main agricultural soil properties were assessed using the

statistical (weighted) average in the topsoil and subsoil. For the production of the maps of C stocks and distribution (FAO, 2007), ArcMap 10.3 was used to join the geometric database with the C stocks. These were ranked into five categories for SOC density (0-14, 14-22, 22-31, 31-61 and 61-236 tons/ha) and five others for SIC (0, 0.1-30, 30-45, 46-74 and 74-200 tons/ha).

The land cover map was that of ESA, at 300 m spatial resolution. The Reference Coordinate System used was a geographic coordinate system based on the World Geodetic System 84 (WGS84) reference ellipsoid. The legend assigned to the global LC map was based on UN-Land Cover Classification System.

Total SOC and SIC stocks were calculated separately for the topsoil (0-0.3m) and subsoil (0.3-1.0 m) using the following equations:

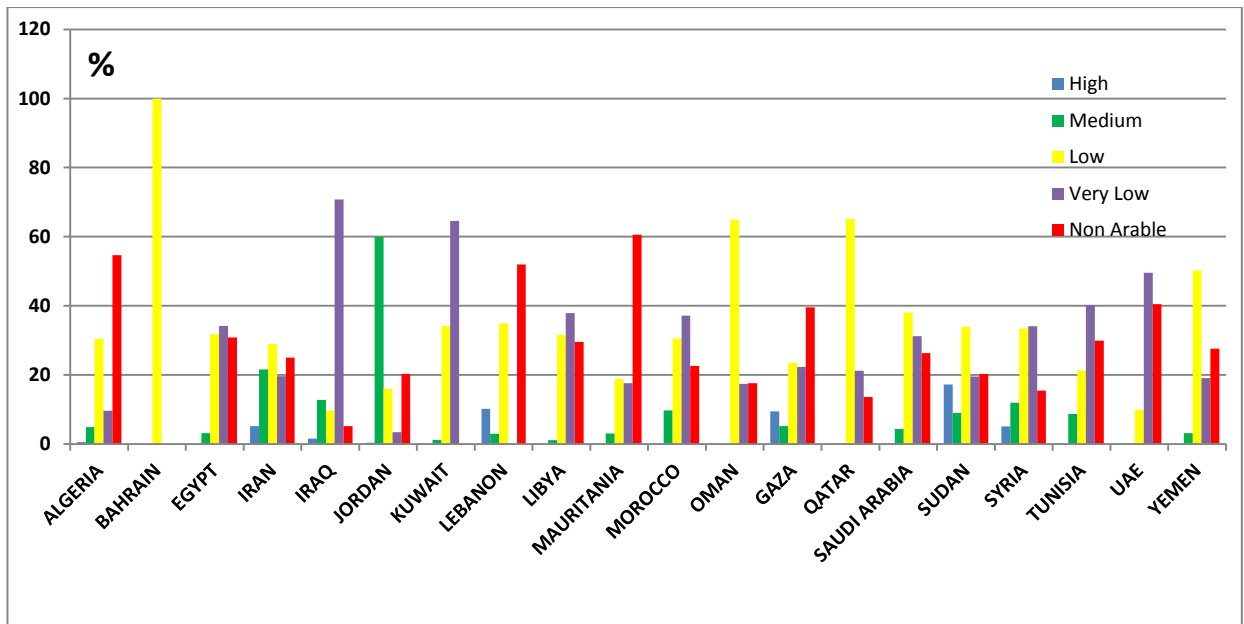
National C Stock (ton) = [Area (m^2)*Depth (m)*Bulk Density (ton m^3)*OC content (%)]/100   (1)

SOC or SIC density (ton ha^{-1}) = Stock in given soil unit (ton)/Soil Unit Area (ha)   (2)

Stocks of SOC under different land cover/land use were evaluated, as well. Since 1990, the European Space Agency, (Climate Change Initiative project), started to produce land cover (LC) maps of the NENA region. The version used in the study corresponds to the second phase of the 2015 global LC (http://maps.elie.ucl.ac.be/CCI/viewer/index.php) with a spatial resolution of 300 m.

3.   Results and Discussion

3.1. Land capability and SOC in NENA region

According to the results based on the land capability model, 40 to 100% of soils in the region fall within the low, very low and non-arable classes (Figure 2). Thus, the proportion of highly and medium productive soils varies between 0% (Bahrain, Qatar, Oman and UAE) and 60% (Jordan). Countries like Iraq, Lebanon, Morocco, Palestine, Somalia, Syria and Tunisia, present between 9 and 20% of highly to medium productive soils. The remaining NENA countries have less than 5% of their lands as high and medium productive. Some of these countries belong to the food insecure nations.

157
158 Figure 2. Distribution of land capability classes (% of total national area) for 20 countries
159 of the NENA region, based on the USDA model (1999) and Digital Soil Map of the World
160 (FAO, 2007).
161

162 The soil productivity concept is based strictly on soil properties. But, with the lack of

163 water in drylands and the prevalence of rainfed agriculture, the soil cannot show its full

164 potential for food production. Similarly, irrigation with brackish water restricts crop

165 productivity due to the development of secondary soil salinity. With properly managed

166 irrigation, the medium productive lands can provide moderately good harvests. For

167 instance, our field observation in Jordan showed that a large area of productive lands was

168 cropped with barley, not because of land suitability, but due to low rainfall (< 200 mm). In

169 drought affected years, the land is converted into grazing area for small ruminants

170 following crop failure to make the minimal profit from the exploitation.

171

172 The low productivity of the soil is reflected in the SOC contents. The accumulation of

173 SOC in NENA region is refrained by the high mineralization rate (Bosco et al., 2012).

174 Climate change and recurrent drought events affect SOC sequestration in the soil. It is

175 estimated that a rise in temperature of 3 °C would increase the emission of carbon dioxide

176 by 8% (Sharma et al., 2012).

177

178 Among the soil properties affecting SOC, the clay and calcium carbonate contents are

179 most relevant. High clay content tends to counteract the decomposition of SOC, as found

180 in clay soils of Morocco and in Vertisols of northern Syria (FAO and ITPS, 2015). But,

181 the dominant soil classes (Table 1) characterized by sandy and sandy loam textures, are

182 subject to fast decomposition. Next to the clay texture, the presence of calcium carbonate

183 decreased the decomposition of composted organic material in sub-humid coastal Lebanon

184 (Al Chami et al., 2016). This slower turnover of organic matter was explained by the low

185 porosity and prevalence of micropores in soil macro-aggregates (Fernãndez-Ugalde et al.,

186 2014).

187

188 3.2. Mapping of soil carbon stocks

189 Based on the mapping of SOC density (ton ha^{-1}), 69% of the regional soils have a density

190 below to 30 tons ha^{-1} (Figure 3), value considered as a threshold for C deficient soils

191 (Batjes and Sombroek, 1997). This could be linked to the arid conditions prevailing in the

192 region with flat lands and limited humid mountain areas. Consequently, the majority of

193 the countries of NENA region presents moderate to relatively low total stocks of SOC.

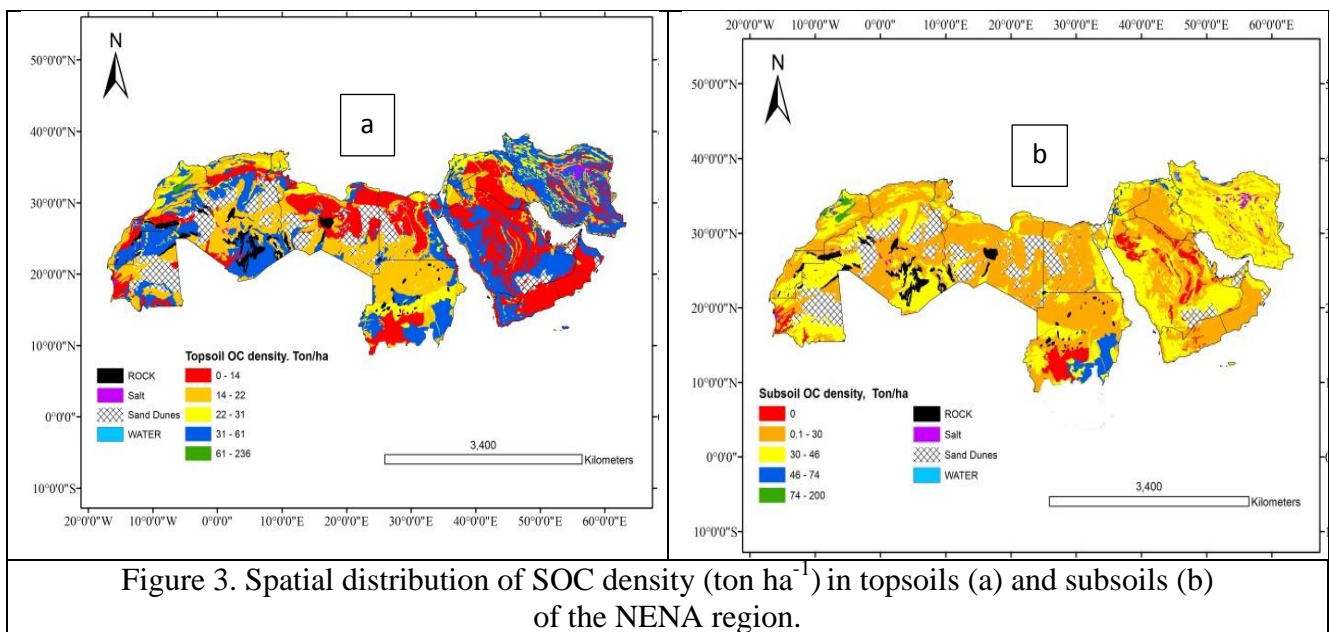



Figure 3. Spatial distribution of SOC density (ton ha^{-1}) in topsoils (a) and subsoils (b)
of the NENA region.

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195 This is especially relevant to the Gulf countries, Iran, Tunisia and Morocco, with values

196 below 221 Mega tons (Figure 4). Such low OC sequestration potential can be explained by

197 the sparse natural vegetation and the reliance on irrigation to produce food and feed crops.

198 A regional implementation plan for sustainable management of NENA soils appeared in

199 2017 (http://www.fao.org/3/a-bl105e.pdf). In fact, the total stocks in the topsoils (0-0.3 m)

200 of NENA countries, represent only 4.1% of the world global stock

201 (https://drive.google.com/drive/folders/1454FhX_p2_GxjZT-fsi0-RncL2QpSN).

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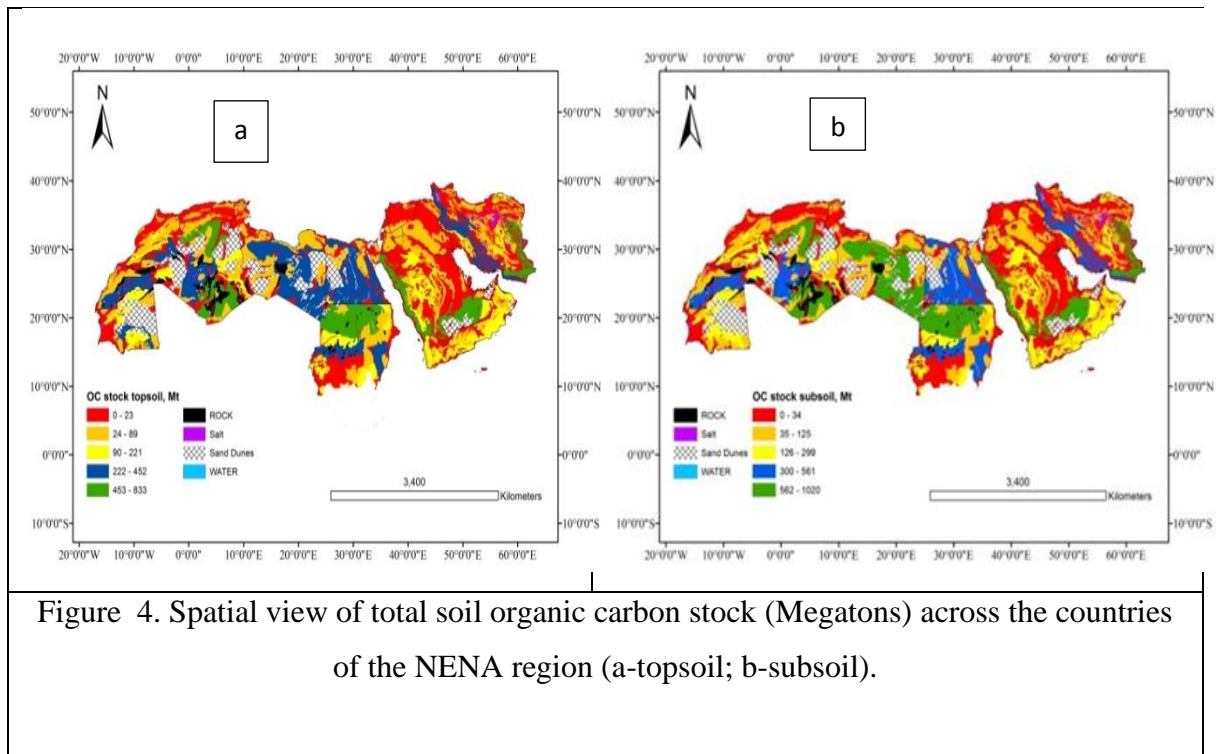


Figure 4. Spatial view of total soil organic carbon stock (Megatons) across the countries of the NENA region (a-topsoil; b-subsoil).

A comparison has been undertaken between the FAO methodology, adopted in the present work (two soil layers: 0-0.3 m; 0.3-1 m), and a previous study where the soil profile was divided into six depths down to 2 m (Hengl et al., 2014). Both approaches agree about the NENA region (SOC content: 1-2% and SOC stock: 20-204 ton ha^{-1}), as confirmed by the Global Soil Organic Carbon Map (http://www.fao.org/global-soil-partnership/pillars-action/4-information-and-data/global-soil-organic-carbon-gsoc-map/en/). The global gridded soil information based on machine learning (SoilGrid250m) contains 1.6 billion pixels also predicted SOC density but the arid and semi-arid zones are under measured and thus pseudo observations based on expert knowledge were introduced to predict the SOC content in the soil at seven standard soil depths (Hengl et al., 2017).

The choice of scale when using or producing soil maps may lead to uncertainty in small countries and fragmented land use (Darwish et al., 2009). The coarse scale adopted in this work (1:5 Million) could be a source of uncertainty. Practically, this corresponds to a polygon of 0.5 cm x 0.5 cm (area < 0.25 cm^2), the equivalent of an area of 6.25 km^2 on the ground. To test this, the results of the current estimation (1:5 Million) of SOC stocks in Lebanon, were compared with the large scale mapping at 1:50,000 for Lebanon (Darwish et al., 2006). The FAO scale gave an overestimation of 11.2% in the topsoil, underestimation of 16.4% in subsoil and a 14.4% underestimation in the whole profile

223 (Darwish and Fadel, 2017). Therefore, the level of mapping uncertainty falls within the
224 reported diagnostic power of soil maps, with a map purity of 65-70% (Finke et al., 2000).
225 In our study, the matching reached 83.6-88.2%. Any loss of information related to small,
226 non-mappable soil units in coarse scale mapping (1:5 Million or 1:1 Million) could be
227 rectified by national and sub-regional large scale soil mapping (1:50,000 and 1:20,000).
228
229 Another source of error can be associated with the SOC content in soil classes or major
230 groups from the DSMW (FAO, 2007). The level of uncertainty in the assessment of the
231 SOC density in NENA countries depends on the variability of SOC, as suggested by the
232 standard deviations of the means (Figure 1). Therefore, the SOC content is the major
233 source of variability for the SOC density at the soil class level. Cambisols and Fluvisols
234 present the largest standard deviation, caused by a long land use history and large
235 anthropogenic impact. Subsoil is less subject to pedoturbation and direct human influence,
236 thus SOC content has lower variability.
237
238 3.3. Land cover mapping and stocks of SOC
239 Based on the land cover map of ESA, the bare lands correspond to 80% of the whole
240 NENA region (Figure 5). Grassland, sparse vegetation cover and rainfed agriculture
241 represent 4.39 -5.27%. The irrigated crops do not exceed 0.66% of the total area,
242 distributed in limited cultivated area (Figure 5). The NENA region possesses a land area
243 about 15 million km^2, with a total population exceeding 400 million inhabitants (about 6%
244 of world population) but with only 1% of the world's renewable water resources
245 (https://www.slideshare.net/FAOoftheUN/plenary1-keynote-speech-16dec2013az). In fact,
246 the irrigated area corresponds to 247.5 m^2 per capita. This could be one of the reasons for
247 the high dependency on imported food, exacerbated by demographic pressure, rapid
248 urbanization, water scarcity and climate change (FAO, 2015).

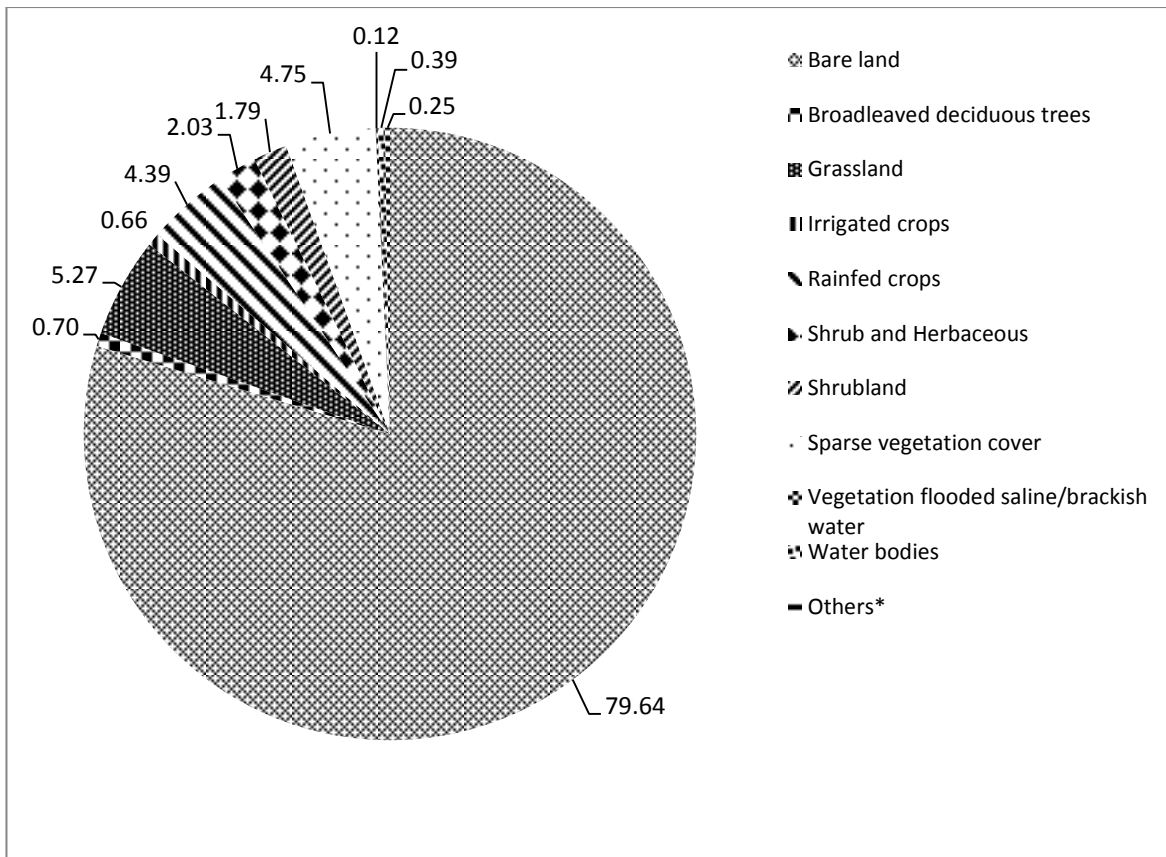
Bare land
Broadleaved deciduous trees
Grassland
Irrigated crops
Rainfed crops
Shrub and Herbaceous
Shrubland
Sparse vegetation cover
Vegetation flooded saline/brackish water
Water bodies
Others*

*Others: Mixed trees, Needle-leaved, Evergreen trees and Urban

Figure 5. Proportion of main land cover (% total land area) and land use in NENA region. (http://maps.elie.ucl.ac.be/CCI/viewer/index.php, 2015)

The combination of SOC stock map with the land cover map showed a significant effect of land cover on SOC stocks in NENA region. As can be expected, shrublands, sparse vegetation and bare lands gave the smallest values, between 14 and 26 ton ha^{-1} (Figure 6). In a mixture of shrublands and herbaceous vegetation, the SOC increases to 40 ton ha^{-1}. The highest density (30 and 60 ton ha^{-1}) is found under forest stands.

Despite the expected impact of frequent plowing, the soils under mixed trees and irrigated crops have higher SOC density than rainfed crops. This could be linked to the higher biomass produced under irrigated conditions in these water-limited areas. The highest SOC stock is observed under evergreen forests whose area is very limited (3380 km^2 corresponding to 0.02% of the total area). Surprisingly, the stock found under urban soils ($\approx$ 30 tons ha^{-1}) is moderate. This could be related to the urban encroachment on prime soils. Between 1995 and 2015, rapid urban growth caused the loss of over 53 Million tons of soils, 16% of which correspond to prime soils (Darwish and Fadel, 2017). The assessment of SOC content in NENA region showed a decline of OC content in topsoil by

271 up to 1% between 2001 and 2009 (Stockman et al., 2015). Land cover change is

272 considered as the primary agent of change of SOC, followed by temperature and

273 precipitation.

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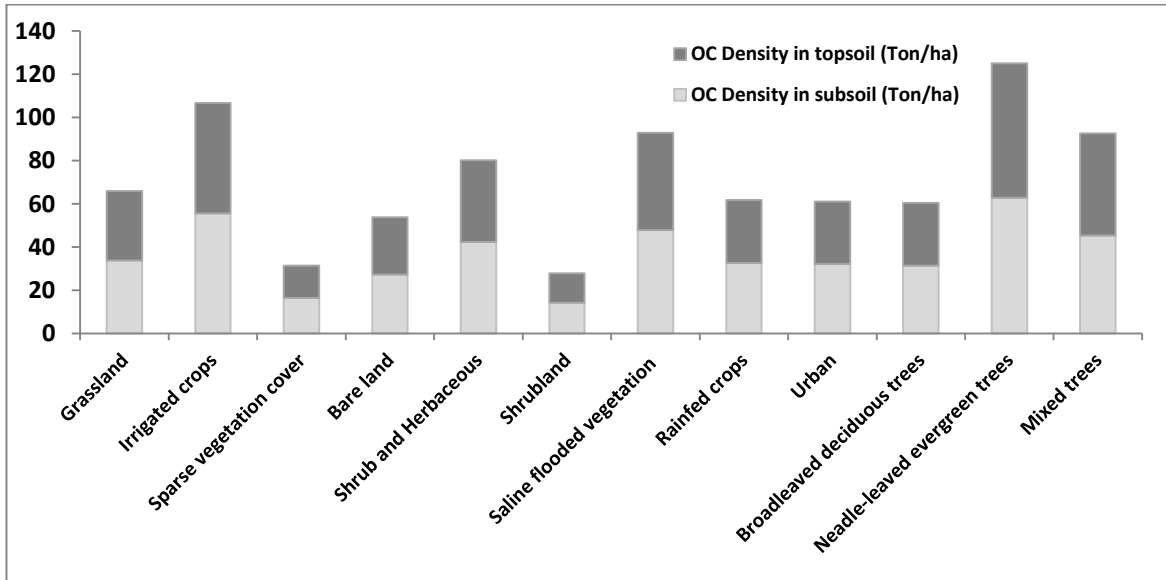
276 Figure 6. SOC density (tons ha^{-1}) in the topsoil (0-0.3 m) and subsoil (0.3-1.0 m),
277 calculated from the FAO DSMW (FAO, 2007), under corresponding land cover
278 (http://maps.elie.ucl.ac.be/CCI/viewer/index.php).

279 In addition to the stocks of SOC in relation to land cover-land use, the stocks of SOC and

280 SIC were established per country (Figure 7). The range of SIC stocks is very wide, from

281 less than 25 tons ha^{-1} (Gaza subsoil) to 450 tons ha^{-1} (Bahrain subsoil), while that of SOC

282 vary between $\approx$ 20 tons ha^{-1} (Bahrain subsoil) and 45 tons ha^{-1} (Sudan subsoil). Based on

283 the stocks of SIC in the subsoils, the countries are separated into three groups. The first

284 (Bahrain, Oman, Egypt, Saudi Arabia, UAE and Yemen) is dominated by calcareous

285 parent materials, with values in the subsoil exceeding 200 tons ha^{-1} (Figure 7). The second

286 group (Kuwait, Libya, Iran, Iraq, Algeria, Qatar, Morocco and Tunisia), presents a SIC

287 density between 100 and 200 tons ha^{-1}. Finally, the third group (Gaza, Jordan, Lebanon,

288 Mauritania, Syria and Sudan) has less than 100 tons ha^{-1}.

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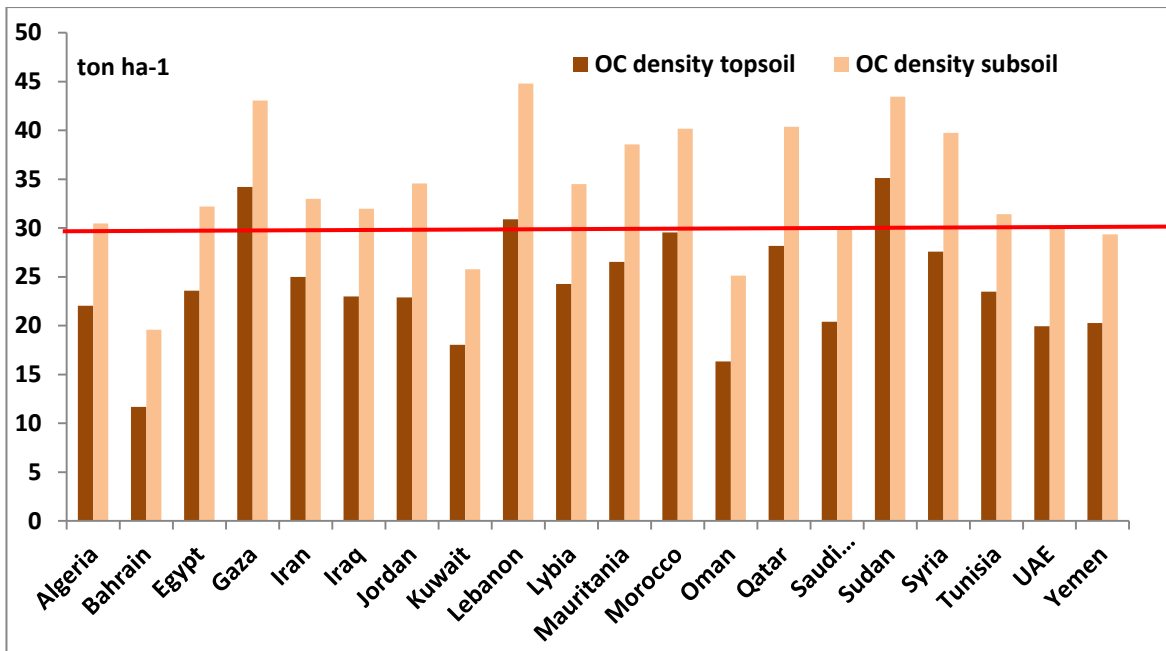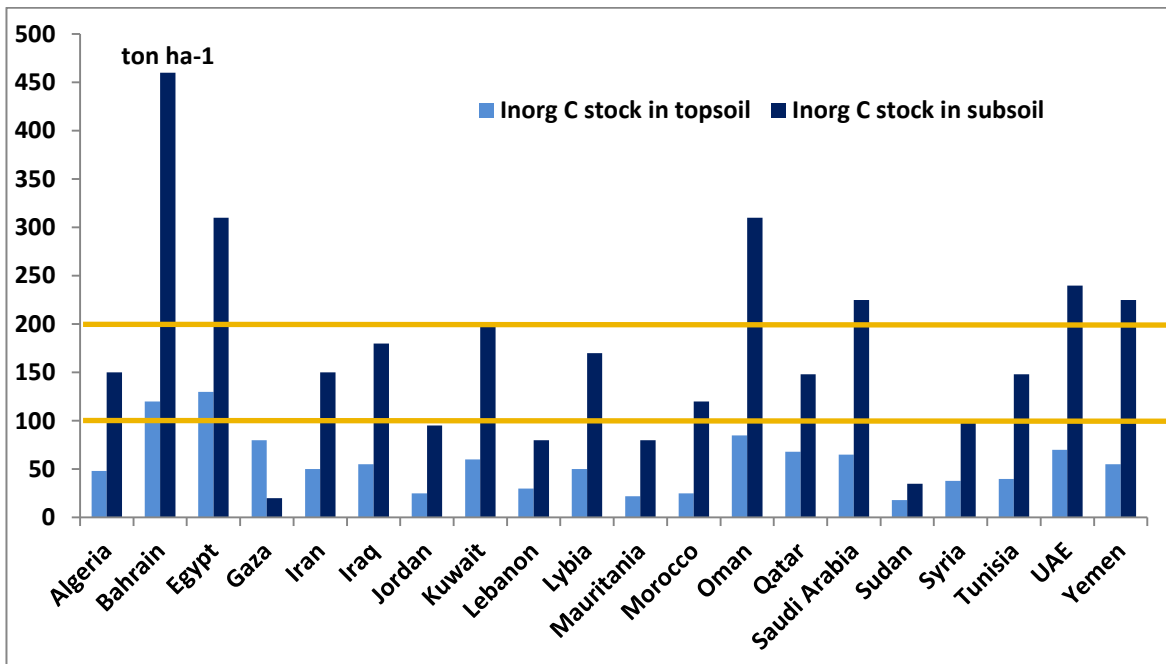
Figure 7. Soil organic carbon and soil inorganic carbon density (tons ha^{-1}) in the topsoil (0-0.3 m) and subsoil (0.3-1.0 m) of the 20 countries in the NENA region. The red line represents the threshold for organic carbon, and the yellow lines correspond to the limits of classes for inorganic carbon.

3.3. Challenges of carbon sequestration in NENA agro-ecosystems

Climatic conditions characterized by wetting/drying cycles, a long dry and hot season (Boukhoudoud et al., 2016) promote the decomposition of SOC. Further, frequent cultivation, irrigation with saline water, and soil salinity rise in coastal areas exert significant effects on soil microbial functional properties. For instance three months after the application of glyphosate-based herbicide under olive in coastal Lebanon, lipase

activities significantly decreased (Boukhoudoud et al., 2017). Soil classification and SOC mapping help identifying hot spots that need to be improved or require special management measures and bright spots with satisfactory C accumulation levels that need to be protected. In this section, major practices affecting SOC will be presented followed by a discussion of preventive and remediation measures.

3.3.1. Tillage and SOC

Tillage practices contribute to the vulnerability of soils to water erosion. If not properly managed, some 41 million hectares in NENA region would be affected by water erosion (FAO and ITPS, 2015). The erosion of soil surface layers can affect the soil carbon in two possible ways. The greater exposure of carbonates to climatic elements could increase the loss of SIC to the atmosphere and ground water. Compared to stable soils, the higher decomposition of SOC in eroded soils decreases the productivity of cultivated crops and can reduce SOC stock, if not properly managed (Plaza-Bonilla et al., 2015).

A possible measure to reduce the risk of erosion is the no-tillage practice. No-tillage coupled with mulching, to reduce weed development and omit herbicide application, as part of conservation agriculture (CA), aims to return more plant residues to the soil, enhance C sequestration, increase soil aggregates, improve water infiltration and protect soil carbon from decomposers (Palm et al., 2014). Through a modification of common practices, such as the frequency and depth of tillage, changes in the SOC could be promoted in most soils. Experiments conducted by ICARDA, Syria, showed that no-tillage performed well in terms of energy and soil conservation (Plaza-Bonilla et al., 2015). Elsewhere, in Palestine soil conservation was found to pay, with a net profit 3.5 to 6 times higher than without conservation measures (FAO and ITPS, 2015). In dryland regions, agricultural activities based on CA practices are beneficial as crop residues are left on the soil surface (Plaza-Bonilla et al., 2015). The presence of residues would protect the soils from high evaporation, water and wind erosion. This is especially relevant to soils that are sensitive to degradation, such as the very shallow Lithosols, the periodically swelling and shrinking Vertisols, Gypsic Yermasols (Aridisols), the poorly-structured Solonchaks and Solonetz, the sandy-textured Arenosols, and the desert soils (Xerosols).

Major constraints facing soil conservation measures, in East Mediterranean, were due to knowledge and perception, prevailing practices of complete removal as hay or forage and

336 sometimes burning of residues after harvest, land tenure and type of landscape (FAO,

337 2012; FAO and ITPS, 2015). These factors are socio-economic in nature, rather than

338 scientific. They are related to the ability of growers to accept new techniques and adopt

339 them. In many situations, the transfer from the research stations to the farmers was not

340 smooth. For instance, CA was successfully tested in experimental stations in Morocco and

341 Lebanon, but several social and technical barriers prevented it from reaching farmers

342 (Mrabet et al., 2012; FAO, 2012).

343

344 A debate has been taking place about the effect of no-tillage on SOC. Many authors agree

345 that under CA, SOC increases near the soil surface, but not necessarily throughout the

346 profile. A study compared 100 pairs, where no-tillage has been practiced for over 5 years.

347 The absence of tillage lead to higher C stocks (0-0.3 m soil depth) in 54% of pairs, while

348 39% showed no difference in stocks (Palm et al., 2014). In the absence of tillage, the

349 slower decomposition of residues would result in higher C accumulation on the soil

350 surface. Over a period of 5 years, zero tillage promoted an increase in SOC equal to 1.38

351 Mg ha^{-1} as compared to the conventional tillage in northern Syria (Sommer et al., 2014).

352

353 3.3.2. Agricultural practices and SOC

354 Practices such as the application of N fertilizers, organic amendments, incorporation of

355 residues and crop rotations, influence the levels of SOC. In soil mining practices without

356 minimal input of fertilizers, the lack of available nutrients makes most crops entirely

357 reliant on the mineralization of accumulated SOC (Plaza-Bonilla et al., 2015). In East

358 Africa, 14-years of continuous cultivation without any input decreased SOC from 2% to

359 1% (Sharma et al., 2012). The application of N fertilizers was associated with increased

360 levels of soil C, as compared to the absence of N fertilizers (Palm et al., 2014). In a 10-

361 year rotation of wheat-grain legume in northern Syria, the application of nitrogen

362 fertilizers to the cereal caused a notable increase of SOC in the top 1m of soil, equal to

363 0.29 Mg ha^{-1} year^{-1} (Sommer et al., 2014). Similarly, in semi-arid Lebanese area (Anti-

364 Lebanon mountains), legumes (*Vicia* sp., *Lathyrus* sp.) intercropped with barley (*Hordeum*

365 *vulgaris*) significantly increased SOC in cherry orchards (Darwish et al., 2012). Roots of

366 cover crops contributed some 140 and 250 kg ha^{-1}season^{-1} of organic matter (OM) against

367 95-665.7 kg ha^{-1}season^{-1} of OM for the aboveground parts.

368

The effects of crop rotations on SOC are related to the amounts of above and belowground biomass produced and retained in the system. In a study conducted in semi-arid northern Syria, a 12-year rotation gave higher SOC in wheat-medic (12.5 g SOC kg^{-1} soil) and wheat-vetch (13.8 g SOC kg^{-1} soil) rotations, as compared to continuous wheat (10.9 g SOC kg^{-1} soil) or wheat-fallow (Masri and Ryan, 2006). In this rainfed system, the introduction of a forage legume (vetch/medic) with wheat, over a decade, was able to significantly raise the level of SOC. Further, the combination of crop rotations and no-tillage was found to sequester more C than monocultures (Palm et al., 2014). One means of building up biomass is through winter cover crops. Their beneficial impact on C sequestration and water infiltration has been demonstrated. The presence of a cover crop on the soil surface protects the soil against erosion. Still, more research is needed about the best species to be used, the optimum termination strategies of the cover crop as well as the best date and density of planting and best management practices of consequent crops (Plaza-Bonilla et al., 2015). The choice of cover crops in NENA region is crucial as these can compete with the main crop for the limited water resources.

In poor dryland regions, especially in the rainfed agricultural systems, some practices hinder the accumulation of SOC. Overall, crop residues serve as fodder or for household cooking or heating, leaving little plant material on the soil surface. Even animal dung is used as cooking fuel in many regions. The low SOC content could be improved by increasing the crop residues produced and incorporated. Such an approach requires the application of fertilizers in order to avoid the depletion of soil nutrients (Plaza-Bonilla et al., 2015). By removing residues, animal dungs and crops, no residues are left in the soil except roots. In the absence of fertilizers, these practices can mine the soil N and over the years the pool of nutrients in the soil can be imbalanced and depleted.

Some authors question the validity of remediation measures to promote SOC accumulation in most of the NENA region. Results from research stations in Egypt and Syria provide evidence to the contrary. In a trial in north-east Cairo, Egypt, the irrigation of a sandy soil with sewage water, for 40 years, changed its texture to loamy sand (Abd el-Naim et al., 1987). This modification of the soil texture leads to a significant improvement of the soil physical properties. Further, within the same long-term trial, the irrigation with sewage water, for 47 years, increased SOC to 2.79%, against 0.26% in the control (Pescod and

402 Arar, 2013). This rather slow accumulation could be related to the sandy soil texture and
403 to the input of the organic matter in labile, soluble forms.

404

405 The addition of more stable composted materials was tested in semi-arid north Syria. The
406 amount of compost, 10 Mg ha^{-1} every two years, needed to raise the SOC, was too large in
407 these rainfed systems. This amount is larger than the compost available in these
408 conditions. Rather than relying on composts, the authors found that a combination of
409 reduced tillage and a partial retention of crop residues moderately increased SOC
410 (Sommer et al., 2014). The quality of residues seems to affect the SOC on the short-term
411 but on the medium-term it is the quantity that matters (Palm et al., 2014).

412

413 3.3.3. Impact of irrigation on agricultural soils
414 The irrigated land represents a minor fraction of agriculture in NENA region, but irrigated
415 crops are essentially found on prime soils (Figure 4). Frequent wetting of irrigated soils
416 make them more likely to lose C as compared to dry soils. But, this partial loss is
417 compensated by higher biomass production and greater OM inputs from roots, even if
418 residues are removed. Lack of moisture limits soil mineralization (Sharma et al., 2012).
419 Irrigated soils promote intense microbial activity and a rapid decomposition of SOC. In
420 the fertile region of Doukkala, Morocco, known for producing wheat and sugar beet, a
421 decade of irrigated farming decreased soil organic matter by 0.09% per year (FAO and
422 ITPS, 2015). This loss could have been reduced through the incorporation of crop
423 residues. But, in these mixed farming systems, aboveground residues are consumed by
424 farm animals.

425

426 The irrigation of soils in NENA region is expected to affect the SIC. Dryland soils were
427 considered to contain equivalent stock of SIC as SOC (Sharma et al., 2012). But higher
428 SIC than SOC were found in this study, notably in the subsoils. Despite this large stock,
429 there is a major knowledge gap regarding the effects of land use and management on the
430 dynamics of SIC. This is especially relevant to the irrigation with calcium or sodium-
431 enriched groundwater (Plaza-Bonilla et al., 2015). In these conditions, the formation of
432 calcium carbonate could be accompanied by some release of carbon dioxide while the
433 development of sodicity can cause irreversible SOC loss.

434

435 4. Conclusions

436 NENA area consisting of 14% of the earth surface contributes only 4.1% of total SOC

437 stocks in topsoil. The soil resources of NENA region are developed under dry conditions

438 with prevailing of rainfed agriculture. The majority of lands in NENA countries are of low

439 productivity. The current mapping of SOC density showed that 69% of soil resources

440 represent a SOC stock below 30 tons ha^{-1}, indicating the soils of NENA region are not

441 enriched with OC. Highest stocks (60 tons ha^{-1}) were found in forests, irrigated crops,

442 mixed orchards and saline flooded vegetation. This means that SOC can be increased in

443 the soils of the NENA region under appropriate and sustainable soil management

444 practices. The moderate density ($\approx$30 tons ha^{-1}) in urban areas indicates land take by urban

445 growth and expansion on prime lands. The stocks of SIC were higher than SOC density,

446 due to the calcareous nature of soils. In subsoil, the SIC stock ranged between 25 and 450

447 tons ha^{-1}, against 20 to 45 tons ha^{-1} for SOC. The OC sequestration in the NENA region is

448 a possible task to mitigate climate change and sustain food security despite the hostile

449 climatic conditions and poor land stewardship and governance. Practices of conservation

450 agriculture (no-tillage, intercropping and agro-pastoral system, winter cover crops, proper

451 rotation) could be effective in reducing evaporation, water and wind erosion and

452 promoting aboveground and belowground biomass production. Land cover and land use

453 affected the amounts of SOC retained in the soil ecosystem. A good result was achieved in

454 Lebanon through winter cover crop consisting of fruit trees-legume-barley intercropping

455 system. Knowledge gaps exist with respect to the effect of irrigation on SOC and SIC.

456 Constraints facing soil conservation measures and carbon sequestration in the NENA

457 region can be faced with awareness raising and capacity building at the level of

458 stakeholders and decision-makers. Sustainable soil management can contribute to alleviate

459 the pressure on soil resources, improve SOC sequestration and maintain soil resistance to

460 degradation.

461

462 5. Acknowledgements

463 This paper was supported by the FAO, GSP-ITPS, UNESCWA and CNRS Lebanon

464 within a land degradation assessment and SOC mapping project related to food security.

465

466 6. References

467   Abd Elnaim E. M. Omran, M. S. Waly, T. M. and El Nashar, B. M. B.: Effects of
468   prolonged sewage irrigation on some physical properties of sandy soil, *Biolog. Wastes,* 22,
469   269-274, 1987.

470   Al Chami, Z. Bou Zein Eldeen, S. Al Bitar L. and Atallah T.: Decomposition of olive-mill
471   waste compost, goat manure and Medicago sativa in Lebanese soils as measured using the
472   litterbag technique, Soil Res., 54, 191-199, 2016.

473   Atallah, T. Jamous, C. Debs, P. and Darwish, T.: Biosolid recycling to enhance carbon
474   sequestration in mountainous Lebanese conditions, Leb. Sci. J., 13, 69-79, 2012.

475   Batjes, N. H. and Sombroek, W. G.: Posibilities for carbon sequestration in tropical and
476   subtropical soils. Global Change Biol., 3,161-173, 1997.

477   Bosco S., Di Bene, C., Bonari E.: The effect of crop management on soil organic matter in
478   the carbon footprint of agricultural products. 8th Int. Conf. on Life Cycle assessment in
479   the agri-food sector, Saint-Malo, France, 1-4 October 2012, 2012.

480   Bosco, S., Di Bene, C., Galli, M., Remorini, D., Massai, R., and Bonari, E.: Soil organic
481   matter accounting in the carbon footprint analysis of the wine chain, Int. J. Life Cycle
482   Assess., 18, DOI 10.1007/s11367-013-0567-3, 2013.

483   Boukhoudoud, N., Gros, R., Darwish, T., and Farnet Da Silva A.M.: Agriculture practice
484   and coastal constraint effects on microbial functional properties of soil in Mediterranean
485   olive orchards. Europ. J. of Soil Sc., 67, DOI: 10.1111/ejss.1234, 2016.

486   Boukhdoud, N., Farnet Da Silva, A. M., Darwish, T., and Gros, R.: Olive mill waste and
487   glyphosate-based herbicide addition to olive grove soils: effects on microbial activities and
488   their responses to drying/rewetting cycles. Soil Use and Manage., DOI:
489   10.1111/sum.12367, 2017.

490   Cerdå A., Gonzalez Penaloza F., Santin C., and Doerr S.H. Land abandonment, fire
491   recurrence and soil carbon content in the Macizo del Caroig, Eastern Spain. Geophy. Res.
492   Abstracts 14, EGU2012-14331, 2012.

493   Darwish, T. Faour, Gh. and Khawlie, M.: Assessing Soil Degradation by Landuse-Cover
494   Change in Coastal Lebanon. Leb. Sci. J. 5, 45-59, 2004.

Darwish, T. Khawlie, M. Jomaa, I. Abou Daher, M. Awad, M. Masri, T. Shaban, A. Faour, Gh. Bou Kheir, R. Abdallah, C. and Haddad, T. (Eds). Soil Map of Lebanon 1/50000, Publications CNRS-Lebanon, Monograph Series 4, 1-367, 2006.

Darwish, T., Abou Daher, M., Jomaa, I, and Atallah, T.: Soil organic carbon stock estimation in Lebanese territories. 10th International Meeting on Soils with Mediterranean Type of Climate. CNRS-Lebanon, Book of Extended Abstracts, 113-118, 2009.

Darwish, T., Atallah, T., Francis, R., Saab, C., Jomaa, I., Shaaban, A., Sakka, H., and Zdruli P.: Observations on soil and groundwater contamination with nitrate, a case study from Lebanon-East Mediterranean, Agr. Water Manage., DOI 10.1016/j.agwat.2011.07.016, 2011.

Darwish, T.M. Jomaa, I. Atallah, T. Hajj, S. Shaban, A. Zougheib, R. and Sibai Ouayda, F.: An agropastoral system as a practice to enhance organic matter in Lebanese inland mountainous soils. Leb. Sci. J., 13, 1-14, 2012.

Darwish, T., and Fadel, A.: Mapping of Soil Organic Carbon Stock in the Arab Countries to Mitigate Land Degradation. Arab J. Geosci., 10, DOI.org/10.1007/s12517-017-3267-7, 2017.

Elhadi, M.Y.: Postharvest technology of food crops in the Near East and North Africa (NENA) region, in: Crops: Growth, Quality and Biotechnology, 643-664, WFL Publisher, Meri-Rastilan tie 3 C, 00980 Helsinki, Finland, 2005.

FAO: The digital soil map of the world. Food and Agriculture Organization of the United Nations, Version 3.6, completed January 2003 and updated 2007 (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116), accessed 20 December 2017.

FAO: Country Study on Status of Land Tenure, Planning and Management in Oriental Near East Countries Case of Lebanon, FAO, RNE, SNO, Cairo, Egypt, 161p., 2012.

FAO: Regional Overview of Food Insecurity - Near East and North Africa: Strengthening Regional Collaboration to Build Resilience for Food Security and Nutrition, Cairo, Egypt, FAO, 2015.

FAO: Voluntary Guidelines for Sustainable Soil Management, Food and Agriculture Organization of the United Nations Rome, Italy, http://www.fao.org/3/a-bl813e.pdf, accessed November 17, 2017.

526   FAO and ITPS: Status of the World's Soil Resources (SWSR) – Main Report, Food and

527   Agriculture Organization of the United Nations and Intergovernmental Technical Panel on

528   Soils, Rome, Italy, 2015, www.fao.org/3/a-i5199e.pdf accessed 13 December, 2017.

529   Fernandez-Ugalde, O. Virto, I. Barre, P. Apesteguia, M. Enrique, A. Imaz, M. J. and

530   Bescansa, P.: Mechanisms of macroaggregate stabilisation by carbonates: implications for

531   organic matter protection in semi-arid calcareous soils, Soil Res., 52, 180-192, 2014.

532   Finke, P. Hartwich, R. Dudal, R. Ibanez, J. Jamagne, M. King, D. Montanarella, L. and

533   Yassoglou N.: Georeferenced Soil Database for Europe, Manual of Procedures, Version

534   1.1. European Soil Bureau, 2000.

535   Guo, LJ. Lin, S. Liu, T. Q. Cao, C.G. Li, C. F.: Effects of conservation tillage on topsoil

536   microbial metabolic characteristics and organic carbon within aggregates under a rice

537   (Oryza sativa L.)-wheat (Triticum aestivum L.) cropping system in Central China, PLoS

538   One 11:e0146145, 2016.

539   Hengl, T., de Jesus, J. M., MacMillan, R. A., Batjes, N. H., Heuvelink, G. B M., Ribeiro,

540   E., Rosa, A. S., Kempen, B., Leenaars, J. G. B., Walsh, M. G., Gonzalez, M. R.:

541   SoilGrids1km-Global Soil Information Based on Automated Mapping. PLoS ONE 9,

542   e105992, DOI:10.1371/journal.pone.0105992, 2014.

543   Hengl, T., Mendes de Jesus, J., Heuvelink, G. B. M., Ruiperez Gonzalez, M., Kilibarda,

544   M, Blagotić, A, et al. : SoilGrids250m: Global gridded soil information based on machine

545   learning. PLoS ONE 12(2): e0169748. https://doi.org/10.1371/journal.pone.0169748,

546   2017, accessed 20 February 2017.

547   Lal, R.: Soil erosion and the global carbon budget, Env. Int., 29, 437-450, 2003.

548   Masri, Z. and Ryan, J.: Soil organic matter and related physical properties in a

549   Mediterranean wheat-based rotation trial. Soil Tillage Res., 87, 146–154, 2006.

550   Mrabet, R. Moussadek, R. Fadlaoui, A. and van Ranst, E.: Conservation agriculture in dry

551   areas of Morocco. Field Crops Res., 132, 84-94, 2012.

552   Pescod, M. B., and Arar, A.: Treatment and use of sewage effluent for irrigation.

553   Butterworths. https://books.google.com.lb/books, ISBN: 1483162257, Pages 211-212, 2013.

554 Plaza-Bonilla, D. Arrúe, J. L. Cantero-Martínez, C. Fanlo, R. Iglesias, A. and Álvaro-
555 Fuentes, J.: Carbon management in dryland agricultural systems. A review. Agronomy
556 for Sustain. Develop. 35, 1319-1334, 2015.

557 Sharma, P. Abrol, V. Abrol, S. and Kumar, R.: Climate change and carbon sequestration
558 in dryland soils, in Tech open access book, chapter 6. 26 pages.
559 http://dx.doi.org/10.5772/52103, 2012, accessed last time 31 July 2018.

560 Sommer, R., Piggin, C., Feindel, D., Ansar, M., van Delden, L., Shimonaka, K., Abdalla,
561 J., Douba, O., Estefan, G.,. Haddad, A., Haj-Abdo, R., Hajdibo, A., Hayek, P., Khalil, Y.,
562 Khoder, A., and Ryan, J.: Effects of zero tillage and residue retention on soil quality in
563 the Mediterranean region of northern Syria. Open J. of Soil Sci. 4,
564 DOI:10.4236/ojss.2014.43015, 2014.

565 Stockmann, U. Padarian, J. McBratney, A. Minasny, B. deBrogniez, D. Montanarella, L.
566 Young Hong, S. Rawlins, B. G. Damien, J.: Global soil organic carbon assessment.
567 Global Food Security, 6, 9-16, 2015.

568 USDA: Land capability classification, NRCS-USDA, 1999.

569 von Grebmer, K. Bernstein, J. Hossain, N. Brown, T. Prasai, N. Yohannes, Y. Patterson,
570 F. Sonntag, A. Zimmermann, S. M. Towey, O. and Foley, C.: Global Hunger Index: The
571 Inequalities of Hunger, Washington, DC, International Food Policy Research Institute,
572 Bonn, Welthungerhilfe, and Dublin, Concern Worldwide, 2017.

573 Yu, L. Dang, Z. Q. Tian, F. P. Wang, D. and Wu, G. L.: Soil organic carbon and inorganic
574 carbon accumulation along a 30-year grassland restoration chronosequence in semi-arid
575 regions (China), Land Degrad. Develop., 28, 189–198, 2017.