Impacts of land use and topography on soil organic carbon in a Mediterranean landscape (north-western Tunisia)

Donia Jendoubi[1, 2], Hanspeter Liniger[1] and Chinwe Ifejika Speranza[2]

[1] Centre for Development and Environment (CDE), University of Bern, Bern, 3012, Switzerland
[2] Institute of Geography, University of Bern, Bern, 3012, Switzerland
Correspondence to: Donia Jendoubi (Donia.jendoubi@cde.unibe.ch)

Abstract:

This study evaluates the impact of land use and topographic features (slope and aspect) on soil organic carbon (SOC) within the Wadi Beja watershed in north-western Tunisia. A soil spectral library was set up to assess the variation in the SOC for 1440 soil samples from four land use types (field crops, permanent crops, forest, and grazing land), three slope categories (flat, moderate, and steep) and two aspects (north- and south-facing). For field crops, only one factor – slope – significantly affected SOC, with SOC content in north-facing areas appearing to be higher in flat areas (0.75%) than in hilly areas (0.51%). However, in south-facing areas, SOC content was also higher in flat areas (0.74%) than in hilly areas (0.50%). For permanent crops, which were inter-planted with field crops, the slope significantly affected SOC content, which improved to 0.97% in flat north-facing and 0.96% in flat south-facing areas, scoring higher than hilly south- and north-facing areas (0.79%). In the grazing land use system, both of the investigated factors – aspect and slope – significantly affected the SOC content, which was significantly higher in flat areas (north-facing: 0.84%, south-facing: 0.77%) than in hilly areas (north-facing: 0.61%, south-facing: 0.56%). For the forest, none of the factors had a significant effect on SOC content, which was higher in flat areas (north-facing: 1.15%, south-facing: 1.14%) than in steep areas (1.09% in north-facing areas and 1.07% in south-facing areas). This study highlights the ability of visible and near-infrared (VNIR) spectroscopy to quantify C in diverse soils collected over a large diverse geographic area in order to indicate that calibrations are feasible, and therefore, assessing the variation of SOC content under land use and topographic features (slope and aspect) will result in better sustainable land management planning.

Keywords: soil organic carbon – land use – spectroscopy – topography – north-western Tunisia

1. Introduction:

Land degradation is a major challenge for Mediterranean arid and semi-arid ecosystems (Hill et al., 2008). In Tunisia, human activities are responsible for land degradation through deforestation, overgrazing, removal of natural vegetation, and agricultural practices that exacerbate soil erosion (Sarraf et al., 2004). Long-term anthropogenic pressure from agricultural use (Kosmas et al., 2015), together with abiotic factors such as climatic and topographical variability (Scarascia-Mugnozza et al.,

34 2000), create diverse situations for which it is difficult to draw generally valid assumptions concerning
35 SOC distribution and its determinant factors (Jobbagy and Jackson, 2000).

36 Furthermore, soil quality degradation contributes to the deterioration of other land resources (e.g.
37 water and vegetation) (Karamesouti et al., 2015). Soil degradation processes include biological
38 degradation (e.g. soil fertility and soil fauna decline), physical degradation (e.g. compaction, soil
39 erosion, and waterlogging), and chemical degradation (e.g. acidification nutrient and depletion), which
40 are mostly caused by agricultural practices (Diodato and Ceccarelli, 2004; Post and Kwon, 2000). There
41 are both natural and human-induced causes of soil degradation (Bhattacharyya et al., 2015).

42 The soil quality concept has been proposed for application in studies on sustainable land management
43 (Doran, 2002). When using the term "soil quality", it must be linked to a specific function. In this study,
44 soil quality is seen in relation to soil conservation in agricultural systems, which aim to maintain the
45 capacity of soil to function as a vital living system for sustaining biological productivity, promoting
46 environmental quality, and maintaining plant and animal health (Doran and Zeiss, 2000).

47 To measure soil quality, minimum data sets have been suggested that allow a detailed description
48 through the inclusion of soil chemical and physical indicators (Lal, 1998). However, integrative
49 indicators are more appropriate for preliminary studies, as they efficiently provide insights into general
50 soil quality. Soil organic matter (OM) is one such integrative measure of soil quality, influencing soil
51 stability, soil fertility, and hydrological soil properties. OM plays a crucial role in soil erosion: when the
52 erosion removes surface soil, the OM and clay vanish, resulting in a decline in soil fertility and
53 biological activity, and in soil aggregation (Wolfgramm et al., 2007). In soils with high calcareous silty
54 amounts and in the absence of clay, OM is particularly important with regard to the soil's physical
55 properties (e.g. soil structure, porosity, and bulk density), which again determine erodibility (Hill and
56 Schütt, 2000).

57 Mediterranean soils are characterized by low amounts of OM, which results in soil fertility decline and
58 structure loss (Van-Camp et al., 2004). Furthermore, SOC is variable across land use (Brahim et al.,
59 2010), and most agricultural soils are poor in OM, often comprising less than 1% (Achiba et al., 2009;
60 Parras-Alcántara et al., 2016; Muñoz-Rojas et al., 2012). In Mediterranean soils, loss of OM leads to a
61 reduction in root penetration, soil moisture, and soil permeability, which in turn reduces vegetation
62 cover and biological activity, and increases runoff and risk of erosion (Stanners and Bourdeau, 1995).

63 Tunisia has one of the highest SOC depletion rates among Mediterranean countries (Brahim et al., 2010).
64 Its low soil fertility is considered a sign that inappropriate land management systems are predominant
65 in the country (Hassine et al., 2008; Achiba et al., 2009). In north-western Tunisia, soils are mostly
66 derived from an alteration of carbonate sedimentary parent material (marl, limestone, clay), cultivated
67 under rainfed conditions to produce cereal crops (wheat and barley) (Hassine et al., 2008). This form of

2

68 cultivation decelerates the mineralization of OM through a series of unsustainable practices including
69 deep ploughing in spring and summer, stubble ploughing in autumn to protect wheat from Fusarium,
70 and various tillage operations preceding sowing (Hassine et al., 2008). This relatively intensive soil
71 cultivation, accompanied by the practice of an annual application of phosphate and nitrogen fertilizers,
72 is at the root of the decrease in OM content following stimulation of microbial activity (Álvaro-Fuentes
73 et al., 2008).

74 Understanding the above dynamics and SOC distribution as influenced by land use systems and
75 topographic features is critical for assessing land use management planning (Kosmas et al., 2000). SOC
76 contents are influenced by topographic features and climate variation, specifically temperature and
77 water (García Ruiz et al., 2012).

78 Currently, the north-western region of Tunisia is enduring extensive field crop monoculture and land
79 degradation owing to population increase, inappropriate land management, and rough topographic
80 features. Much of the cropped land is unsuitable for agriculture and degrades quickly. The impacts of
81 agricultural practices and topography on nutrient cycling and ecological health, however, have not
82 been studied extensively in the Tunisian northwest region.

83 Due to this dispute, SOC contents measured over time can establish the long-term productivity and
84 possible sustainability of a land use system. In a nutrient-poor system, SOC can play an important role
85 in the stability, quality, and fertility of the soil. Farmers and land use planners are therefore interested
86 in land use management that will enhance soil carbon content.

87 The aim of this study is to quantify SOC content and evaluate the factors that affect SOC variation,
88 specifically the mechanisms affecting differences in SOC distribution patterns along different land use
89 systems and topographic features (slope and aspect) in a Mediterranean ecosystem dominated by
90 agricultural activities in north-western Tunisia.

91 Information on soil quality is crucial for improving decision-making around efficient support of
92 sustainable land management. Thus, methods are needed for fast and inexpensive prediction of
93 important soil quality indicators such as SOC. The potential of diffuse reflectance spectroscopy in the
94 visible and near infrared (VNIR) range for fast prediction of soil properties in a non-destructive and
95 efficient way has been demonstrated by a number of studies (Amare et al., 2013; Shiferaw and
96 Hergarten, 2014; Shepherd and Walsh, 2002).

97 We are not aware of any study evaluating the impacts of topographic features (slope and aspect) or
98 existing land use systems on SOC dynamics in Mediterranean agricultural soils, specifically in Tunisia,
99 based on an accurate and consistent database such as a soil spectral library.

Most soils in north-western Tunisia are exposed to water erosion, which is provoked by poor cover, cultivation practices, and hilly topography. The Wadi Beja watershed was selected because it comprises a variety of degraded areas and areas where soil and water conservation practices (SWC) are applied. It is the most productive and extended cereal area in Tunisia, and faces serious risks associated with monoculture production of field crops under inappropriate land management practices. Some new practices, such as agroforestry, were introduced into the region in the 1980s, along with permanent crops such as olive and almond trees.

The first research objective was to build a soil spectral library in order to apply it to the Wadi Beja watershed, as there was no accurate or valid soil database for the studied region or even for the whole country. The second objective was to examine the distribution of SOC under the different slopes, aspects, and land use systems. The third objective was to investigate, specifically, two hypothesis: (1) Land management practices under different abiotic factors (e.g. topography) influence soil SOC variation. (2) Ecosystems are more sensitive to soil degradation (SOC loss) on steep and south-facing slopes than on gentle and north-facing slopes.

2. Materials and Methods:

2.1. Study area

The study area, the Wadi Beja watershed, lies at 36°37'60" N and 9°13'60" E in north-western Tunisia. Upstream of Wadi Beja is the Amdoun region, and downstream the junction with Wadi Medjerdah in the Mastutah region. Wadi Beja is a tributary of the Wadi Majerdah, the most prominent river in Tunisia (figure 1).
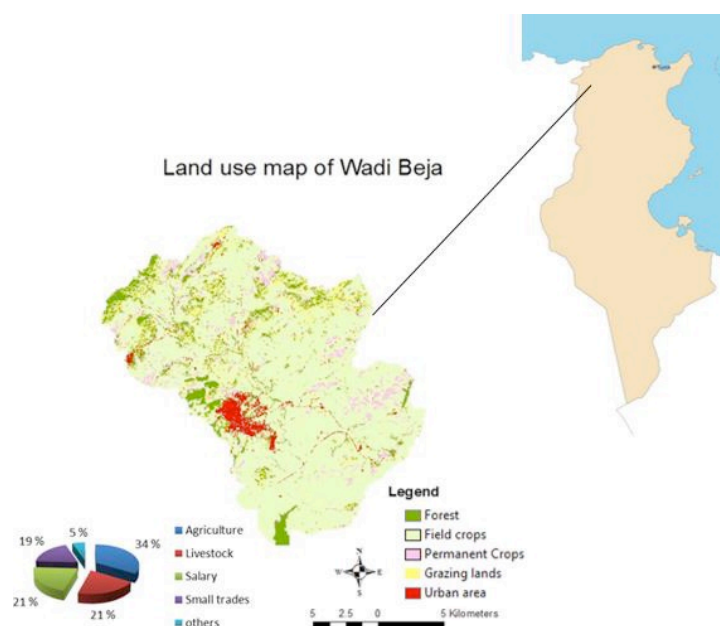
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Figure 1. Characterization of household income, location and land uses of the study area, Wadi Beja watershed, north-western Tunisia. Source: Jendoubi et al., 2019

The watershed (about 338 km²) covers diverse topographic features, with an elevation ranging from 110 m a.s.l to nearly 750 m a.s.l; slopes range from flat (0-8%) to moderate (8-16%) and steep (>16%) areas, with 64% having a steep slope and 36% a moderate slope. Annual rainfall is irregular and varies from 200 mm to 800 mm. Early October to the end of April (late autumn to early spring) is considered the rainy season (AVFA, 2016). During the summer it is very dry and hot. The maximum temperatures are recorded at the end of July and range from 38°C to 44°C. Minimum temperatures are recorded at the end of December and fall between 6°C and 8°C (AVFA, 2016). In the Beja region, the population is mainly rural (56%), with 48.5% being active in the agricultural sector. Agriculture remains the main source of household income (55%, including livestock) (figure 1). Nearly 78% of rural households live entirely off their farms (AVFA, 2016). There are three types of farming systems: extensive (83%), intensive (6%), and mixed (11%). Five different land use systems (LUS) have been defined: field crops (71%), grazing lands (10%), forest (9%), permanent crops (7%), and built-up areas (3%).

The current soil types in the study area are vertisols, which cover 46% of the total area, isohumic soils (23%), brown calcareous soils (12%), and regosols (10%). Rendzinas soils, lithosoils, hydromorphic soils and fersiallitic soils also exist, covering small areas that add up to less than 9% according to the agricultural map of Tunisia.

Land management in the study area is similar in relation to land preparation, organic amendments, crop rotation, and mulching (stubble, roots). Mineral fertilizers have been applied for several decades, and cropland – the most common land use – has been used for monoculture of cereal crops such as wheat and barley.

2.2. Methods

2.2. 1. Land use change history

A land use system (LUS) is defined as a sequence of goods and services obtained from land, but can involve particular management interventions undertaken by the land users as well. It is generally determined by socio-economic market forces, as well as the biophysical constraints and potentials imposed by the ecosystems in which they occur (Nachtergaele et al., 2010).

This study investigated four land use systems – field crops, permanent crops, forest plantation, and grazing land – in order to assess their effects on the variation of SOC (table 1). Built-up areas and roads were excluded. We used atmospherically corrected Landsat Surface Reflectance data images (Bands 4-5, 7 and 8) from 1985, 2002, and 2016 to derive the land use maps, in order to evaluate the changes over that time period (Jendoubi et al., 2019).

The Landsat scenes were selected from among all those available in the green season (out of harvesting) for the corresponding years; we considered only those with less than 20% of cloud cover overall and without clouds on the study site area. Unsupervised classification was carried out for the images in order to define the major land use systems. Following this, a validation based on ground truth data was made in order to confirm the generated land use maps and assess their accuracies.

Table 1 illustrates substantial land use and land cover change (LULC) in the Wadi Beja watershed after 1980.

Table 1. The five major land use and management classes studied in the Wadi Beja watershed, Tunisia

Aggregated land use classes	1985		2002		2016	
	%	km²	%	km²	%	km²
Field crops	82.1	272.7	76.4	254.0	71.0	236.2
Grazing lands	9.3	30.9	10.2	33.7	9.7	32.2
Forests	3.9	13.1	7.7	25.6	8.9	29.6

Permanent crops	**3.4**	11.2	**4.2**	14.1	**7.3**	24.4
Built-up areas	**1.3**	4.5	**1.5**	4.9	**3.1**	10.0
Total	**100**	332.4	**100**	332.4	**100**	332.4

Field crops constituted the predominant land use type, accounting for approximately 82% in 1985 and 71% in 2016. Plantation forest also increased from 3.9% in 1985 to 9% of the watershed in 2016. In 1980, to remedy the degrading effects of monoculture of annual cropping, deforestation, and overgrazing on pastures and forests, a programme developed by ODESYPANO (Office Development Sylvo-Pastoral Nord Ouest) and financed by the World Bank implemented some conservation activities including development of permanent vegetative cover using olive trees and sylvo-pastoral management. An agroforestry (agro-sylvo-pastoral) system was introduced in 1982 as an alternative programme for development and conservation in the region. This system included converting annual cropping into a combination of annual crops inter-planted with olive trees (in this study classified as "permanent crops"). This area increased from 3.4% in 1985, when it was introduced for the first time in the region, to 7.3% in 2016. The local farmers took this alternative as they believed that their soils had become poor and no longer gainful for annual crop production. Grazing land remained almost unchanged in terms of area, as it is spread over badlands, barren lands, and riverbanks with a high concentration of eroded and poor soils.
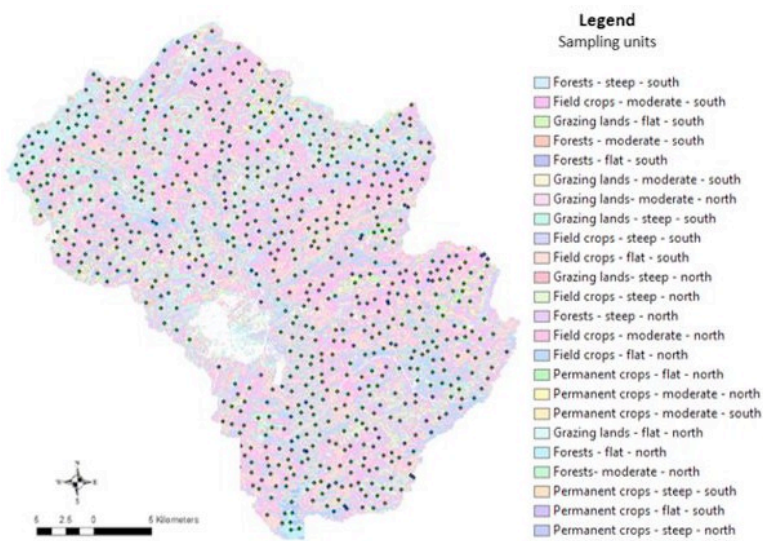
2.2.2. Soil sampling

We selected four land use systems (LUS) (excluding built-up areas), three slope classes, and two aspect classes to study their interrelations and their effects on SOC. The LUS were forests, field crops, permanent crops, and grazing land (table 1). Aspect and slope units were derived from Lidar DTM, aligned, and resampled to 30m. Slope categorization was based on the FAO soil description guidelines (Barham et al., 1997). The slope categories were grouped into three: flat, moderate and steep. Aspect was categorized into two classes: north and south. Details of slope and aspect categories are presented in table 2.

Table 2. Slope and aspect

Slope (%)	Aspect (azimuth degrees)
0 to 8 (Flat)	0 to 90, 270 to 360 (North)
8 to 16 (Moderate)	90 to 270 (South)
> 16 (Steep)	

From all slope and aspect classes and different land use systems (LUS), soil samples were collected randomly from the topsoil (0-20 cm). In a factorial randomized design considering the four land use types, three slopes, and two aspects, a total of 24 different sampling units (n=4×3×2) were considered.

201   In total, 1440 soil samples were collected from all the sampling units in the topsoil layer (0-20 cm) using
202   a soil auger (10 cm diameter) with an average of 60 samples per sampling unit.

Legend
Sampling units

- Forests - steep - south
- Field crops - moderate - south
- Grazing lands - flat - south
- Forests - moderate - south
- Forests - flat - south
- Grazing lands - moderate - south
- Grazing lands- moderate - north
- Grazing lands - steep - south
- Field crops - steep - south
- Field crops - flat - south
- Grazing lands- steep - north
- Field crops - steep - north
- Forests - steep - north
- Field crops - moderate - north
- Field crops - flat - north
- Permanent crops - flat - north
- Permanent crops - moderate - north
- Permanent crops - moderate - south
- Grazing lands - flat - north
- Forests - flat - north
- Forests- moderate - north
- Permanent crops - steep - south
- Permanent crops - flat - south
- Permanent crops - steep - north

203
204   **Figure 2.** Location of the soil samples and the sampling design.

205 The sampling design shown in figure 2 summarizes the strategy of the sampling. Sampling units are
206 listed as shown in table 3.

207 **Table 3.** Sampling units with their corresponding number of soil samples

Sampling units	Number of soil samples
Field crops - flat - north	65
Field crops - flat - south	66
Field crops - moderate - north	60
Field crops - moderate - south	62
Field crops - steep - north	57
Field crops - steep - south	59
Permanent crops - flat - north	60
Permanent crops - flat - south	62
Permanent crops - moderate - north	55
Permanent crops - moderate - south	57
Permanent crops - steep - north	63
Permanent crops - steep - south	65
Forests - flat - north	60
Forests - flat - south	54
Forests- moderate - north	57
Forests - moderate - south	60
Forests - steep - north	61
Forests - steep - south	59
Grazing lands - flat - north	60
Grazing lands - flat - south	63
Grazing lands- moderate - north	55
Grazing lands - moderate - south	59
Grazing lands- steep - north	62
Grazing lands - steep - south	59

208
209

210 **2.2.3. Soil analysis and spectral library**
211 The soil spectral library was set according to protocols cited by Shepherd and Walsh (2002), and
212 includes the following steps: (1) representative sampling of soil variability in the study area; (2)
213 establishing the soil reflectance spectral dataset using VNIR spectrometry; (3) selecting a reference

214 dataset to be analysed using traditional soil chemical methods required as reference values (450
215 samples, or 31% of the total, were selected according to their spectral variability); (4) determination of
216 SOC by means of soil chemical analysis (CNS elemental analysis); (5) calibrating soil property data to
217 soil reflectance spectra by applying multivariate calibration models; and finally (6) prediction of new
218 samples using the spectral library.

219 The soil spectral library for prediction of SOC was adjusted using a mug-light for illumination as
220 described by Mutuo et al. (2006). Soil spectral reflectance was measured under standard conditions in
221 the laboratory. Soil samples were air dried (to 30°C) and sieved to pass through a 2 mm mesh. Soil
222 samples of 2 mm thickness were placed into borosilicate Duran glass Petri dishes with optimal optical
223 characteristics. The Petri dishes were placed on a mug-light equipped with a Tungsten Quartz Halogen
224 light source (Analytical Spectral Devices, Boulder, CO). Spectral reflectance readings were collected
225 through the bottom of the Petri dishes using a FieldSpec PRO FR spectro-radiometer (Analytical
226 Spectral Devices, Boulder, CO). Every sample was measured twice, with the sample rotated by 90
227 degrees for the second measurement. The two measurements were averaged, which minimized light
228 scatter effects from uneven particle size distribution on the Petri dish floor. The instrument works with
229 three spectro-radiometers to cover the wavelengths from 350 to 2500 nm at an interval of 1 nm. The
230 fore-optic view was set to 8 degrees. For dark current readings, 25 scans were averaged, while for white
231 reference and soil spectral readings 10 scans were averaged by the spectro-radiometer. Before each
232 sample reading, white reference readings were taken from a spectralon (Labsphere) that was placed on
233 a trimmed Petri dish bottom.

234 Pre-processing of soil reflectance data to decrease the noise present in the data and thus increase
235 robustness of reflectance spectral data is common in VNIR spectrometry, and is especially
236 important in the case of measuring setups that are difficult to control (e.g. due to power fluctuations
237 or different operators during different measuring sessions). The main pre-processing steps conducted
238 were as follows: Spectra were compressed by selection of every 10th nm. Spectral bands in the lowest
239 (350-430 nm) and highest (2440-2500 nm) measurement ranges were omitted due to a low signal to
240 noise ratio (lower than 90). The final number of wavelengths used as model input was 205. Information
241 for these 205 wavelengths was further processed. Steps in the spectral reflectance curves were observed
242 at the spectrometer changeovers. Most likely, this effect resulted from the Petri dishes used as sample
243 holders and their specific index of refraction.

244 When choosing the validation set, care was taken to assure that validation samples were representative
245 for the whole study area. Thus, samples were systematically chosen by selecting from every land use
246 system and under the different (slope and aspect) sampling units. These samples, which constituted
247 31% of the total samples, were selected for chemical analysis, which was used to validate SOC model
248 prediction.

249 Regarding the chemical method, the elemental CNS analyser (vario MICRO tube, Elementar) was used
250 for SOC estimates. For SOC measurement, 1 g soil is pre-treated with 10 drips of H_3PO_4 in order to
251 remove carbonate. The sample is combusted at 1150°C with constant helium flow, carrying pure oxygen
252 to ensure complete oxidation of organic materials. The CO_2 gas is produced and detected by a thermal
253 conductivity detector.

254 A calibration and validation with Partial Least Square Regression were used on cross-validation
255 ("leave one out") in order to ensure simultaneous reduction/correlation of both the spectral
256 information and the concentration data obtained from the chemical analysis.

257 After prediction of the remaining SOC sample values, a set of statistical parameters was applied in
258 order to assess the accuracy of results such as: the coefficient of determination (R^2), which measures the
259 extent to which a regression line estimates real data points; the Residual Prediction Deviation (RPD),
260 which evaluates the quality of a validation; and the Root Mean Square Error of the prediction (RMSEP),
261 which assesses the accuracy of the model. These parameters evaluate the performance quality of the
262 soil spectroscopy model (Rossel et al., 2006).

263 **2.2.4. Statistical analysis**
264 Regarding the soil spectral library analysis, a partial least squares regression (PLS regression) was used
265 in RStudio to validate the spectral prediction model while assessing the coefficient of determination
266 (R2), residual prediction deviation (RPD), and root mean square error of the prediction (RMSEP).

267 After generating the soil spectral library, a test of normality based on Sullivan and Verhoosel (2013)
268 was carried out in order to check the normality distribution of the data.

269 The Statistical Package for the Social Sciences (SPSS 20.0) software was used in order to compare the
270 averages obtained under the different factors. Variance analyses and multiple comparisons (MANOVA
271 test) were carried out to determine the effect of the different factors (land use, slope, and aspect) on the
272 variation of the SOC. Results were significant when $p<0.05$. The interaction effect between the factors
273 was tested using the technique of split file. The results were grouped according to the land use factor
274 and the effect of the slope and aspect were tested for each land use value.

275 Results were presented in histograms using Excel XLSTAT. We then assessed the variation of SOC
276 under the different selected factors.

277 **3. Results**

278 **3.1. Soil spectral library as an integrative indicator of soil quality**
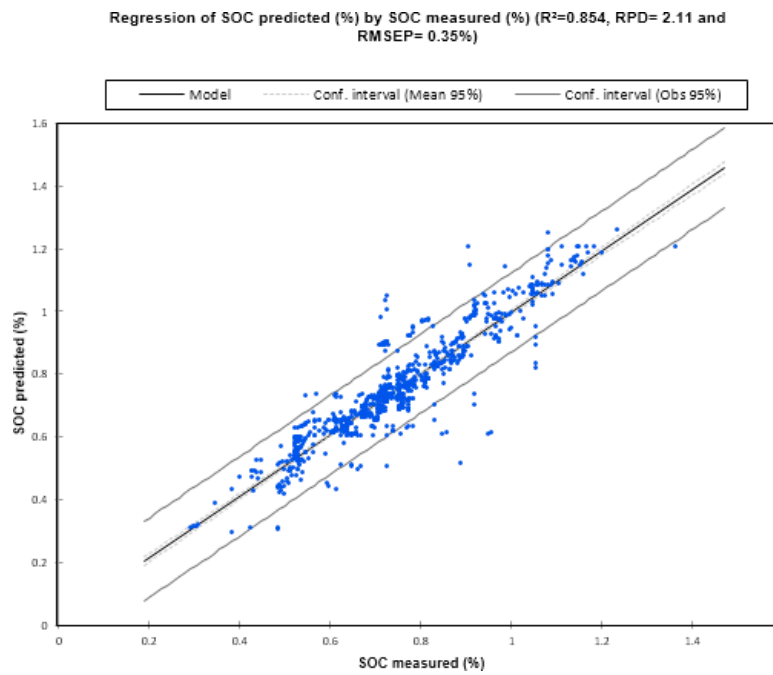279 SOC content was plotted against SOC content predictions as displayed in figure 3.

Regression of SOC predicted (%) by SOC measured (%) (R²=0.854, RPD= 2.11 and RMSEP= 0.35%)

280

Figure 3: SOC values from chemical analysis plotted against SOC prediction.

The obtained spectral prediction model has R2= 0.85, RPD= 2.11, and RMSEP= 0.35%, which was rated excellent for prediction because RPD>2 (Viscarra Rossel et al., 2006). This means that the model is able to determine accurately the SOC content of 85% of the samples. The RPD (2.11>2) also showed that the model developed is of good quality and can be used to predict the remaining spectra and for further development of the spectral library.

Regarding the normality of the data, the test showed a high correlation of 0.95 between the overall data and their corresponding z-scores. Therefore, this means that the data are approximately normally distributed.

3.2. Significance effects of all the variables

A multivariate MANOVA analysis revealed the variables that had statistically significant differences in SOC related to land use systems, slopes, and aspects. Table 4 shows the results of the significance analysis for each of the three variables. The highest significance was reported for land use, followed by slope and aspect.

Table 4. MANOVA results showing the significance of the impact of land use, slope, and aspect for SOC (n= 1440)

	F	Sig.
LUS	395.263	**0.000**
slope	76.505	**0.000**
aspect	11.093	**0.001**

Sig. < 0.05 (statistically significant difference), in bold.
Sig. > 0.05 (no statistically significant difference)

The analysis of the significance of the different variables for each land use type is presented in table 5.

Table 5. MANOVA results regarding significance of all the variables under different LUS.

LUS	Variables	F	Sig.
Forests	slope	1.806	0.176
	aspect	2.931	0.094
Field crops	slope	51.429	**0.000**
	aspect	1.028	0.312
Permanent crops	slope	36.474	**0.000**
	aspect	0.068	0.795
Grazing lands	slope	8.242	**0.001**
	aspect	5.971	**0.017**

Sig. < 0.05 (statistically significant difference), in bold.
Sig. > 0.05 (no statistically significant difference)

For forest land use, no variables were significant, indicating that the variation of the SOC with high contents in those components was not related to slope or aspect. For field crops and permanent crops, only slope had a significant effect on SOC. For grazing lands, both variables (slope and aspect) revealed significant effects on SOC content.

13

3.3. SOC according to land use systems

SOC content for different land use systems is shown in figure 4. The forest LUS had the highest SOC content, with 1.09%. Permanent crops had the second highest values with 0.87% SOC content. The lowest SOC content was found for field crops (0.70%) and grazing soils (0.74%).
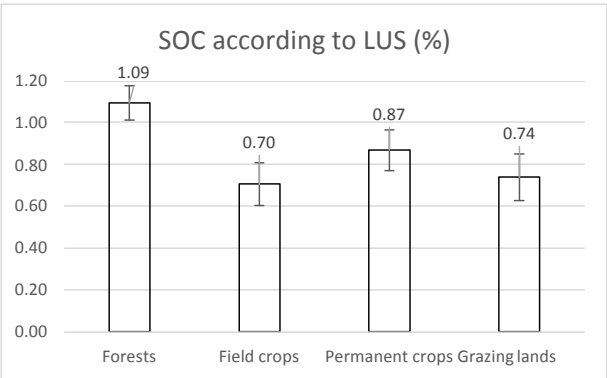
Figure 4. SOC contents according to land use systems in the Wadi Beja watershed, Tunisia.

According to the MANOVA results, land use systems significantly affect SOC content. In the study area, the lowest SOC content was found in field cropping soils (0.70%), and the highest SOC content in the forests (1.09%).

3.4. Impact of slope and aspect on SOC

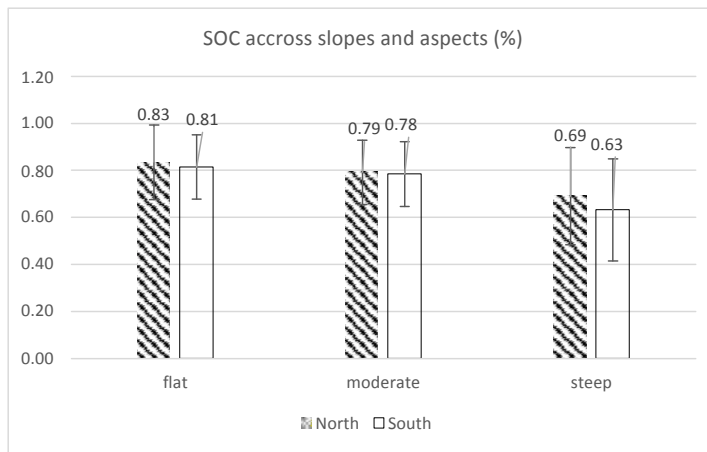SOC accross slopes and aspects (%)

Figure 5. SOC rates according to slope and aspect in the Wadi Beja watershed, Tunisia.

Figure 5 shows the highest SOC content (0.81%-0.83%) on flat slopes and slightly reduced SOC on moderate slopes (0.98%-0.79%). Both flat and moderate slopes revealed no significant difference between north-facing and south-facing slopes (difference <0.02%). The lowest SOC was on steep south-facing slopes with 0.63%, followed by steep north-facing slopes with 0.69% SOC.

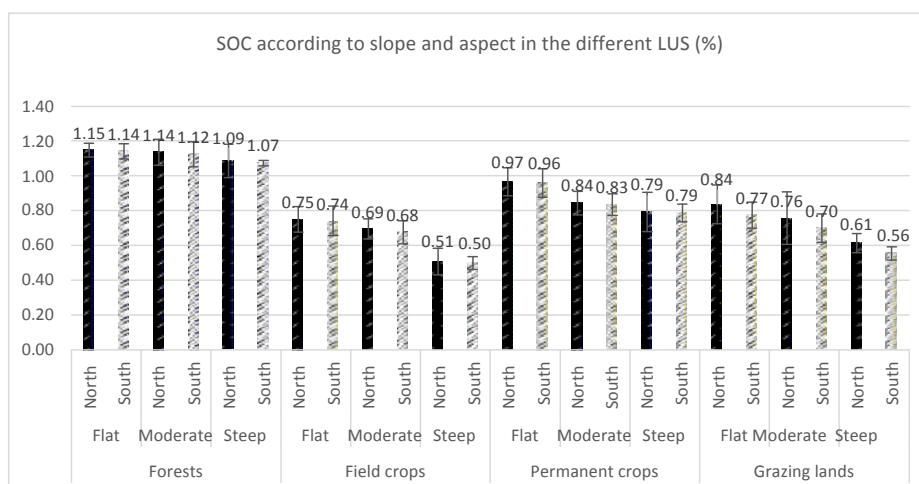**3.5. Impact of land use, slope, and aspect on SOC**

Figure 6. SOC contents according to slope and aspect for the different land use systems.

When evaluating the impact of slopes on SOC variations under the different LUS, the results presented in figure 6 reveal that in forest plantations, the highest SOC content was observed in flat and north-facing areas (1.15%). On moderate slopes in north-facing areas, 1.14% SOC was found, and 1.09% SOC on steep north-facing areas. As previously shown, statistically, the slope has no significant effect on SOC variation under the forest LUS.

For field crops, the highest SOC content was found in flat north-facing areas (0.75%), followed by 0.69% on moderate slopes in north-facing areas and then very low figures of 0.51% on steep slopes in north-facing areas. Figure 6 clearly shows a marked decline in SOC with increased slopes under field crops. For permanent crops, the decrease with increasing slopes is less than that of the field crops. The highest SOC content was found in north-facing areas, first on flat slopes (0.97%), second on moderate slopes (0.84%), and third on steep slopes (0.79%). Finally, on grazing lands, the different slopes showed marked differences. In flat north-facing areas, SOC was 0.84%, while it was 0.77% in flat south-facing areas; in moderate north-facing areas it was 0.76% and in moderate south-facing areas 0.70%; and in steep north-facing areas it was 0.61%, while it was 0.56% in steep south-facing areas.

The MANOVA test showed that aspect has no significant effect on SOC variation for forests, field crops, or permanent crops. Only for grazing land does aspect have a significant effect on SOC variation, with north-facing soils having greater SOC content than south-facing areas. See figure 6 and table 5.

16

348 **4. Discussion**

349 The Mediterranean region is generally characterized by poor soils with low SOC content (around 2%)
350 due to their nature and to being overused by agriculture, which means that they have low carbon inputs
351 from plant residues and low canopied density, and are subjected to inappropriate management
352 practices (Verheye and De la Rosa, 2005; Cerdà et al., 2015).

353 Land management is shown to be a key indicator affecting SOC distribution, influencing topsoil in
354 particular (Ferreira et al., 2012). In Mediterranean areas in particular, land management is a significant
355 factor given the limitations in SOC accumulation. Moreover, high SOC reflects undisturbed soil and
356 high soil quality, as is the case in forest land use (Corral-Fernández et al., 2013).

357 Regarding the soil spectral library, the obtained spectral responses were well correlated, which means
358 that the prediction model is excellent. Some outliers were detected, and their corresponding soil
359 samples were assessed to check the reasons for their reflectance. This differences can be explained by
360 the fact that some spectral responses were influenced by the colour of the soils. Wolfgramm (2008)
361 found that the spectral responses of dark soils give over-predicted values and those of light soils give
362 under-predicted values. In this case, if samples are identified as outliers, the existing spectral library
363 needs to be extended to include all the variable soils. Thus additional reference values from soil
364 chemical analysis have to be obtained and calibration models for an extended reference sample set need
365 to be developed.

366 The study by Hassine et al. (2008) concluded that SOC content does not exceed 2% in north-western
367 Tunisia; our prediction model falls within this amount with a maximum organic carbon percentage of
368 1.2%. This state of low SOC in soils used for agriculture, compared to forests – which have little
369 indication of soil degradation – has been confirmed by various authors (Arrouays et al., 1994; Cerri,
370 1988; Robert, 2002). This low content has negative impacts on the soil structure, which is built mainly
371 by means of mineral colloids; its stability is affected, leading to numerous deficiencies in production
372 and susceptibility to degradation factors. Cereal soils may have acquired a balance between SOC inputs
373 and losses, but at a very low equilibrium level compared to forests, with the latter having less decline
374 in SOC and being protected against erosion, which is the main type of land degradation in the study
375 area (Hassine et al., 2008).

376 Previous studies have shown that SOC can play a significant role in monitoring soil quality related to
377 land use and reduction of soil degradation (Shukla et al., 2006; Hassine et al., 2008). The soil spectral
378 library made it feasible to gain some interpretations and therefore to generate some recommendations
379 for land use planners regarding assessing SOC variability, as an integrative soil quality measure.

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380 The results for the impact of land use on SOC indicate that field crops have the lowest SOC content.
381 This could be the result of land degradation due to inappropriate agricultural management such as
382 intensive tillage, the removal of crop residues, reduced vegetation cover, deteriorated soil aggregation
383 and erosion, and a continuous monoculture system. This finding is coherent with the results of several
384 researchers (Lemenih and Itanna, 2004; Lal, 2005; Muñoz-Rojas et al., 2015; Hamza and Anderson, 2005)
385 who have revealed a significant decline in SOC content in cropland compared to natural forests. Herrick
386 and Wander (1997) found that in annual cropping systems, the distribution of SOC is highly influenced
387 by land management practices such as reduced tillage, rotation, fertilization, and shifting cultivation.
388 Consistent with the study by Hassine et al. (2008) in north-western Tunisia, the reduced OM
389 decomposition rates are a result of intensive agricultural practices: monoculture, tillage on steep slopes,
390 and tillage in wet seasons, in addition to other topographic features, which may lead to a decrease in
391 SOC.

392 Changing annual field crops by inter-planting them with permanent tree crops has increased the SOC
393 of soils under previous annual field crops almost halfway to the level of SOC in forests (0.87%).
394 Intercropping previously mono-cropped fields with tree crops (olive, almond, and pomegranate trees)
395 between 1982 and 1985 significantly increased SOC within 30-35 years. Creating agroforestry systems
396 in this way is considered to have been an appropriate land management intervention in north-western
397 Tunisia. However, some farmers made no changes to their land management, as they did not perceive
398 the advantages of the agroforestry system (Jendoubi and Khemiri, 2018). Yet agroforestry systems are
399 globally recognized, since they are more efficient at capturing and utilizing resources than grassland
400 systems or single-species cropping (Nair et al., 2011).

401 Grazing lands, even though they are not tilled, have a low content of SOC (0.74%), only slightly higher
402 than annual crops (Figure 3). Continued overgrazing and reduction of vegetation cover seem to
403 degrade the soils and their SOC. A low SOC content can persist due to a lack of appropriate grassland
404 management. Open pasture without canopies and weak grass-vegetation cover increase the
405 vulnerability of this land use system to soil degradation and SOC decline. Various studies have shown
406 that the way grazing land is managed affects SOC (Wu et al., 2003; Soussana et al., 2004): overused
407 grazing lands with less vegetation cover are more affected by soil erosion and soil exposure to wind
408 and rain, leading to greater SOC loss. Notably, grassland management strongly affects SOC content,
409 which decreases as grazing intensities increase (Neff et al., 2005).

410 The highest SOC content was found in the forests. The explanation for this is that forest has dense cover,
411 which protects soil from being exposed to any other factors such as erosion, hence the SOC content is
412 less affected. This finding has been confirmed by many authors who have shown that in Mediterranean
413 areas, many forest soils are rich in OM; as a consequence, these soils supply a large input of carbon,
414 and have a low litter decomposition, which means that they are distinguished by high SOC (Lal, 2005;

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415 FAO, 2010), which is highly related to the lower amount of natural and human-induced disturbance in
416 the forests.

417 Regarding the impact of slope on SOC variation, our results show that the higher the slope, the lower
418 the SOC content. Irvin (1996) specified that generally, with increasing slope, OM lixiviation is reduced,
419 mineral is weathered, clay is translocated, and horizons are differentiated.

420 Moreover, topography has a significant impact on soil temperature, soil erosion, runoff, drainage, and
421 soil depth – and hence soil formation. The high SOC variation on hillslopes is explained by the
422 decomposition rates of OM and litter input differences (Yimer et al., 2006).

423 When assessing the results of the impact of aspects on SOC variation, south-facing terrain has lower
424 SOC content than north-facing terrain, which is explained by its exposure to the highest solar radiation
425 and, in particular, the highest temperature during the vegetation period and the long hot summers.
426 This implies high evaporation and a high burn down of OM due to high temperature, less moisture in
427 soils, and consequently a slowdown of the decomposition of OM.

428 In addition, according to our findings, the impact of both slope and aspect on SOC content was very
429 distinct, as indicated statistically by a significant effect on SOC content in the MANOVA. The issue is
430 that steep and south-facing slopes are more sensitive to degradation than other areas, which is
431 explained by the fact that steepness increases runoff and soil erosion, and southern exposure increases
432 evapotranspiration and temperatures, thus decreasing the availability of nutrients, water, and SOC to
433 plants. Apart from differences in land use management, SOC variation is mainly affected by
434 environmental factors in soil along with topographic features (slope and aspect).

435 The literature links temperature and moisture to OM decomposition in soils (García Ruiz et al., 2012;
436 Griffiths et al., 2009). As shown by Garcia-Pausas (2007), in the Mediterranean area, shaded areas such
437 as north-facing or colder southern areas regularly sustain high moisture content for longer and
438 consequently become more fertile and productive, in contrast to south-facing areas, which are exposed
439 to high radiation and thus occasional water deficits.

440 With regard to steepness and aspect, the higher the slope, the more exposed to the south, and the more
441 affected by erosion and different climatic conditions, the lower the SOC content (Yimer et al., 2007;
442 Yimer et al., 2006). Different topographic features are considered to have different microclimatic and
443 vegetation community types and thus significant variations in SOC. Topography (slope and aspect)
444 hence plays a crucial role in relation to temperature and moisture regimes. The temperature is highly
445 influenced by solar radiation, which has a role in soil chemical and biological processes and vegetation
446 distribution (Bale et al., 1998). Hence, the temperature of the soil plays a key role in monitoring the

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447 biomass decomposition rate, and thus affects the SOC distribution, either by delaying or accelerating
448 its decomposition (Scowcroft et al., 2008).

449 From the results of assessing the impact of slope combined with land use, we can see that the highest
450 SOC content was observed in flat areas under all land use systems, and it tended to decrease in steep
451 areas. In general, under all land use systems, we can observe the same tendency for SOC variation, with
452 the highest SOC content in flat positions and the lowest in steep positions.

453 This can be explained by minimal erosion in flatter areas and higher deposition of sediments, resulting
454 in accumulation of SOC. Erosion causes stripping of the soil in hillslope areas. As shown by Yoo et al.
455 (2006), the prevalent portion of SOC is deposited in depositional areas, with hillslopes being more
456 susceptible to sporadic mass wasting events, continuous soil erosion and production, and consequently
457 less SOC storage. In addition, the highest erodibility is related to hilly areas where soils have a tendency
458 to be shallow, coarse in texture, and low in OM, while lower erodibility is observed in flat areas with
459 organic-rich, deep, and leached soils (Lawrence, 1992).

460 From the clear difference in the variation in SOC under forest and field crop land use systems, we
461 interpret that it is the land use factor that dominates SOC distribution rather than the slope factor.

462 In general, steep slopes have a lower SOC content than flat land, as they are more vulnerable to erosion,
463 especially when associated with inappropriate management and overuse (Reza et al., 2016; Bouraima
464 et al., 2016). Cropland in sloping areas is highly vulnerable to water erosion, which leads to extensive
465 soil disturbance, while land use patterns affect vegetation cover, soil physical properties such as SOC,
466 and surface litter. Therefore, this provokes the runoff and soil erosion processes that accompany
467 nutrient loss (Dagnew et al., 2017; Montenegro et al., 2013). Therefore, the extent of nutrient loss differs
468 according to land use systems, as is the case with cereal monoculture in the study site.

469 Hence, in order to improve and maintain soil quality parameters for sustainable productivity, it is
470 crucial to reduce intensive cultivation and integrate the use of inorganic and organic fertilizers.

471 In agricultural areas, continuous intensive cultivation without appropriate soil management practices
472 has contributed to loss of SOC. Kravchenko et al. (2002) and Jiang and Thelen (2004) found that within
473 variability in topography, slope was considered to be a major crop yield limiting factor.

474 Correspondingly, after inter-planting permanent crops with field crops, SOC content was enhanced.
475 Herrick and Wander (1997) showed that after introducing permanent crops, slope significantly affected
476 SOC content.

477 Our results also show less SOC in south-facing areas, and confirm findings from other studies on the
478 interaction effects of slope and aspect on OM decomposition (Griffiths et al., 2009).

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479 According to McCune and Keon (2002), the reason for these results is that slope and aspect play a
480 significant role in solar radiation redistribution, hence the solar radiation heterogeneity on hillslopes
481 leading to differences in soil moisture and temperature. Huang et al. (2015) stated that the SOC content
482 in shaded aspect areas was significantly higher than in sunny aspect areas. Therefore, increases in SOC
483 and OM accumulation are supported by increased moisture and reduced temperature, while decreased
484 soil temperature usually results in decreased OM decomposition rates and litter decay rates
485 (Blankinship et al., 2011).

486 For grazing lands, all the variables (slope and aspect) revealed significant effects on SOC content, as
487 was also shown in the study of Bird et al. (2001). SOC content is generally low, though it is higher in
488 flat areas. This is explained by overgrazing and pressure on the different topographic features, as they
489 are all easily accessible to livestock. Even on steep slopes there is pressure and overgrazing, in addition
490 to the exposure of these areas to erosion by wind and rain. This highlights the susceptibility of this land
491 use system to erosion and deterioration of soil quality.

492 The reason why grazing land use systems are the most sensitive to all the tested variables (slope and
493 aspect) can be explained as follows: in the study area, grazing land was generally open grassland and
494 it is evident that soils are more sensitive in open grassland than under tree canopies, as SOC stocks
495 under tree canopies are in general higher than in open grassland (e.g. Seddaiu et al., 2013). Moreno et
496 al. (2007) also found that the SOC content in the topsoil beneath the tree canopies was "around twice
497 as high as beyond the tree canopy". This can also be related to overgrazing, as shown in a literature
498 review of the effects of overgrazing in the Mediterranean basin (Sanjari et al., 2008; Costa et al., 2012).
499 Furthermore, the semi-arid climate and inclined topography prevailing in Mediterranean grazing lands
500 render ecosystems vulnerable to SOC losses. As shown by Ryan et al. (2008), the higher the level of
501 grazing, or the greater the residue removal, the greater the decline in mean SOC level. The reason
502 behind the decrease in carbon and nutrient cycling is mainly that SOC in grassland is accumulated in
503 roots, which leads to its loss with every removal of aboveground biomass.

504 The most likely clarification for the results obtained on decreased SOC content in steep south-facing
505 areas under the field crops land use system is that soils are affected by soil degradation initiated by
506 inappropriate land management and consequently have weak vegetation cover. This condition makes
507 these soils more sensitive to the south-facing exposition characterized by higher solar radiation and
508 evaporation, and thus decreases soil moisture and biological activity, resulting in SOC loss. Wakene
509 and Heluf (2004) have also indicated that intensive cultivation aggravates OM oxidation and hence
510 reduces SOC content.

511 Therefore, some options for sustainable land management practices can be recommended, such as
512 establishment of enclosures (Mekuria and Aynekulu, 2013), which could be efficient in recovering the

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513   degraded grazing land areas of the watershed. In addition to protecting trees against damage caused
514   by uncontrolled grazing animals by installing fences and trunk protection, mixing of animal species,
515   mostly sheep and goats but also cows and horses, and setting additional fodder provision could be a
516   feature of the summer season.

517   In order to maintain improved soil quality and sustainable productivity in croplands, there is a need to
518   reduce intensive cultivation, agroforestry, and practice of fallow, integrate use of inorganic and organic
519   fertilizers, and pay more attention to the most vulnerable areas (steep and south-facing areas).

520   There are strong indications that agroforestry has been successful in retaining and even improving SOC
521   and soil fertility: the results show that introducing an agroforestry system – e.g. combining an olive
522   plantation with annual field crops – has increased SOC content in the most vulnerable areas. Thus, such
523   types of sustainable land use should be the focus of land managers and land use planners.

524   5. Conclusions

525   Land management can profoundly affect SOC stocks. Application of soil and water conservation measures is crucial for sustaining agricultural fields and preventing or reducing soil degradation.

526   In areas with exceedingly erodible soils, such as those on steep slopes and south-facing zones as shown in this study. Greater efforts to reduce SOC decline are required on steep slopes and south-facing land than in flat areas and north-facing land. However, a further study of the area is recommended, especially land use in combination with other topographic features such as altitude and curvature and their effects on SOC content.

527

528   By far the best option, however, is to identify land management practices that increase C stocks whilst at the same time enhancing other aspects of the environment, e.g. improved soil fertility, decreased erosion, greater profitability, or improved yield of agricultural and forestry products. There are a number of management practices available that could be implemented to protect and enhance existing C sinks now and in the future.

529

530   Since such practices are consistent with, and may even be encouraged by, many current international agreements and conventions, their rapid adoption should be as widely encouraged as possible.

531

532   Finally, this paper contributes towards filling a gap in investigation into the impacts of various land uses on SOC in Tunisia. The results presented in this paper are valid for calibration of further soil spectral libraries in north-western Tunisia; this was the first soil spectral library collated in the country and the methodology can be replicated and applied to other areas. Further studies on SOC variation depending on land use and topographic features are needed to inform sustainable land management in Tunisia.

7. Conflict of Interest Statement

The authors affirm that there are no conflicts of interest regarding the publication of this paper.

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