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## **Role of topography and physico-chemical properties on organic carbon distribution in semi-arid calcareous soils**

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### **Abstract**

Soil represents a significant reservoir of organic carbon within terrestrial ecosystems. Despite considerable research efforts, the factors that control the distribution of soil organic carbon (SOC) remain insufficiently understood, particularly in calcareous soils where recent studies have indicated potential interactions between inorganic and organic carbon pools. The objective of this study was to evaluate the influence of topography and physico-chemical soil properties on the distribution of soil organic carbon (SOC) in a small calcareous catchment cultivated with annual crops under a semi-arid Mediterranean climate (Kamech, Cape Bon, Northeast Tunisia). Soil samples were gathered from all horizons of ten soil profiles, selected to encompass the three primary soil types identified within the study catchment.

As anticipated, the SOC contents were found to be low and to decrease significantly with increasing soil depth. It is noteworthy that significantly higher SOC levels were observed in Vertisols in comparison to Cambisols and Calcisols. The results indicated that clay content was the primary factor influencing SOC distribution in the studied soils. Additionally, the topographical location of the profile was identified as a secondary factor in explaining lateral SOC distribution within the catchment. Furthermore, the study demonstrated a negative correlation between SOC and soil inorganic carbon (SIC), which is an unexpected result for semi-arid environments and requires further investigation.

**Key Words:** Soil organic carbon, rainfed cropland, calcareous soils, semi-arid Mediterranean environment.

## 1. Introduction

Soil is the largest reservoir of carbon after the oceans and the geological formations (Chevallier et al., 2016). Global change, which includes climate and land use change, is expected to greatly modify this reservoir, affecting both soil functionality and the global carbon budget (Martí-Roura et al., 2019; Ramesh et al., 2019). The total soil carbon stock in the first top meter is estimated at 2200 PgC, of which 67 % represents the soil organic carbon (SOC) and 33% represents the soil inorganic carbon (SIC) (Batjes, 2014).

Given its importance in the carbon pool, SOC is considered a primary criterion of soil fertility and carbon budget regulation. For example, Kirschbaum (2000) showed that changing the SOC reservoir by 10% corresponds to approximately 30 years of anthropogenic CO<sub>2</sub> emissions. Therefore, studying the factors controlling SOC storage and dynamics is necessary to target soil quality, agricultural production and climate change mitigation (Minasny et al., 2017).

The SOC pool is the net balance between OC input (via plants and roots) and output (via erosion, leaching or mineralization due to microbial activity) (Ramesh et al., 2019; Basile-Doelsch et al., 2020). It has been shown that SOC pool is controlled by several factors such as climatic factors (Lozano-García et al., 2017), parent material (Barré et al., 2017), soil physico-chemical properties (Hobley et al., 2015), topography (Li et al., 2018), land use (Albaladejo et al., 2013) and land management (Abbas et al., 2020), *i.e.* a set of factors that are often dependent on each other. Recently, Wiesmeier et al. (2019), in their review, stated that the relevance of a factor to control SOC highly depends on the spatial scale considered. They also proposed an overview of the hierarchy of SOC storage's drivers and indicators according to spatial scale. On a large scale, *i.e.* from several square kilometers to global,

these authors identified three main indicators of SOC storage. The first indicator is relative to “mean annual temperature (MAT) and mean annual precipitation (MAP)”, which are known to drive SOC distribution by controlling soil microbial activity and SOC input level into the soil via the net primary productivity (Ramesh et al., 2019; Wiesmeier et al., 2019; Rodrigues et al., 2023). The second is vegetation, which is a key factor in determining the chemical composition of the organic matter incorporated in the soil (Kogel-Knabner, 2017; Basile-Doelsch et al., 2020). For example, forested soils generally have high SOC levels due to the large amount of lignified organic matter (Kogel-Knabner et al., 2017), compared to cultivated soils, which generally have low SOC levels due to inputs of an easily degradable organic matter (Martí-Roura et al., 2019). The third is related to the geological substrate, which is generally a good proxy of soil texture (Rodrigues et al., 2023) and has a potential impact on the stabilization of SOC (Gray et al., 2015). At a more local scale, i.e. from micro-scale to a few square kilometers, the relevance of climate and soil parent material decreases and the following factors are considered as the main drivers in SOC distribution within small catchments: land use and management, topography and soil’s physicochemical properties (Wiesmeier et al., 2019). We briefly examine each of them below and outline the main indicators of SOC storage reported in studies ranging from the intra-plot scale to the catchment scale.

Land use and management (LUM) have an impact on SOC stock and SOC storage potential, either negatively as with monocultures or frequent tillage practices, or positively as with organic amendment or crop rotation (Martí-Roura, et al., 2019; Wiesmeier et al., 2019). Certain agricultural practices, like irrigation, can have opposite effects, as irrigation generally increases soil moisture, primary production and therefore the return of SOC to the soil, but also generally stimulates microbial activity and therefore the mineralisation of SOC (Gillabel et al., 2007).

It is also known that topography has a significant impact on SOC content and dynamics. (Davy and Koen, 2013). The terrain attributes frequently tested as indicators of SOC distribution at the catchment scale are: elevation, slope gradient, upstream area, topographic wetness index, aspect, profile curvature, slope length factor, and stream power (Li et al., 2018; Wang et al., 2023). They were used because they are thought to be good proxies for the processes that drive SOC distribution and storage, such as flow convergence or water accumulation (Wiesmeier et al., 2019). For example, a very high or low soil moisture content reduces oxygen availability, directly impacting microbial activity and impeding SOC decomposition (Rodrigues et al., 2023).

The soil’s physico-chemical properties are factors commonly used to describe the distribution and dynamics of SOC (Gray et al., 2015). Specifically, soil structure has been found to be a main driver of SOC stability at many scales and conditions, with “the (fine) silt and clay content being a key indicator” (Wiesmeier et al., 2019). One explanation is that the fine fraction of soils increases SOC storage since it includes a variety of minerals, which

“favors the physico-chemical protection of SOC as a result of the formation of organo-mineral complexes” (Basile-Doelsch et al., 2020). Other soil parameters, like soil pH, cation exchange capacity (CEC) and major cations (exchangeable  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) were also proposed as relevant properties for SOC storage (Rowley et al., 2018).

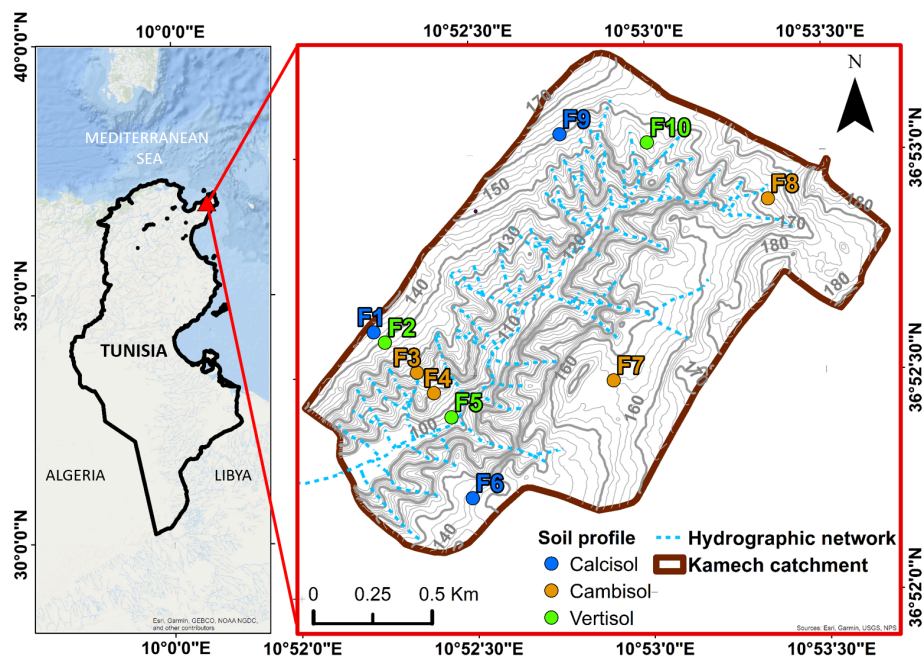
In calcareous soils, SIC content may also play a significant influence on SOC distribution and storage. It is widely known that SIC is more stable than SOC (Sun et al., 2023), with expected millennial SIC mean time residence under natural conditions, recent works (e.g., Cardinael et al., 2019; Sharififar et al., 2023) showed complex interactions between SOC and SIC. For example, Martí-Roura et al. (2019) suggested that the formation of carbonate can protect SOC and improve its stabilization. Three main mechanisms of SOC stabilization by SIC have been described (Rowley et al., 2018): i) the formation of soil aggregates that improve SOC stabilization; ii) the interaction between SOC and cation or mineral; iii) SOC inclusion within pedogenic or biogenic carbonates. On the other hand, the mineralization of the SOC produced an active source of carbon dioxide ( $\text{CO}_2$ ) which can interact with the unlimited  $\text{Ca}^{2+}$  content to produce carbonates ( $\text{CaCO}_3$ ) in calcareous soils with alkaline pH (Sharififar et al., 2023). By studying the relationship between SIC and SOC content in arid and semi-arid areas, some studies report a positive relationship (Wang et al., 2015a; Ibrahim et al., 2019), while others report a negative relationship (Zhao et al., 2016; Lu et al., 2020) and other studies don't show any significant correlation between these two fractions (Lu et al., 2020; Wang et al., 2015b). Sharififar et al. (2023) stated that the positive relationships between organic and inorganic carbon pools have mostly been highlighted in agricultural land and practices, where SOC decomposition contributes to SIC precipitation, while the negative relationships have been reported for non-agricultural areas, where soil redistribution by erosion is considered to be the main driver of the relationship between SIC and SOC.

Despite many efforts to understand SOC storage drivers, the factors that control SOC spatial distribution are still not well understood (Basile-Doelsch et al., 2020), especially in calcareous soils. In this context, this study aims to evaluate and discuss the role of topography and soil physico-chemical properties, including SIC content, on the distribution of SOC in a small calcareous cultivated catchment in the semi-arid Mediterranean region (Cap-Bon, Tunisia) with uniform LUM.

## 2. Materials and Methods

### 2.1. Study area

The Kamech catchment was selected as the study site, covering an area of 263 ha in the northeast of Tunisia (36.88°N, 10.88° E, Fig. 1). This catchment belongs to OMERE’s long-term monitoring infrastructure (<https://www.obs-omere.org/>), extensively described in Molénat et al. (2018) and is included in the OZCAR infrastructure (Gaillardet et al., 2018). 75% of Kamech’s area is occupied by annual rainfed crops, mainly cereals and legumes. LUM are very similar on all cultivated plots in the catchment, with generally three annual tillage operations, very low organic amendments, and some similar patterns of inter-annual rotation between cereals and legumes. The local climate is semi-arid Mediterranean, with an annual precipitation of 620 mm and an annual evapotranspiration of 1300 mm. The terrain in Kamech catchment is hilly, with altitudes varying from 90 meters near the lake to 190 meters in the northeast, (slope gradient quartiles of 0, 6, 11, 18, and 30 %) and a specific catchment erosion rate of around 15 t/ha/year (Inoubli et al., 2017; Ben Slimane et al., 2018). The soils in Kamech catchment are directly developed on marine sedimentary formations from the Middle Miocene (10-15 Ma), which are mainly composed of layers of “slightly calcareous laminated mudstone, with intercalations of hard sandstone” (Molénat et al., 2018). Soil pH generally ranged from 8 to 9, with high clay content and a very low fraction of coarse elements (<1% on average, Khairallah et al., 2025). Based on the classification of the International Union of Soil Science (IUSS Working Group WRB, 2022), the soils are Cambisols, Calcisols, Vertisols, and, more marginally, Regosols.

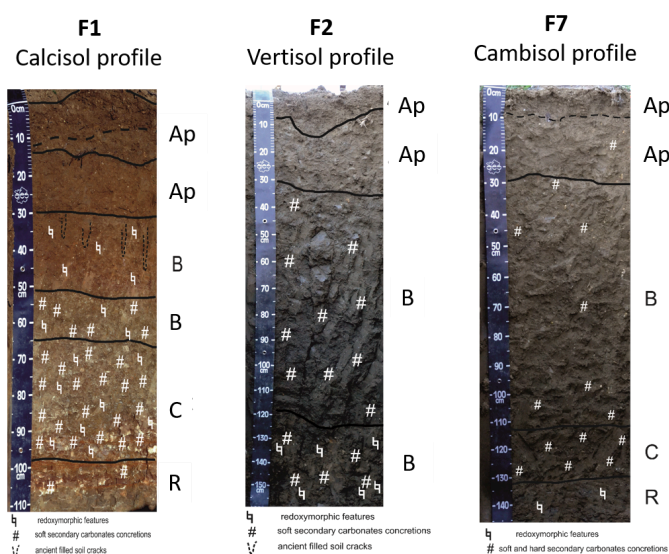


**Fig. 1 Location of the 10 soil profiles studied within the Kamech catchment and illustration of the relief using contour lines.**

## 2.2. Soil sampling and physico-chemical analysis

Ten soil pits were opened in cultivated plots in different parts of the catchment (F1 to F10). Their location was selected to cover the main morpho-pedological characteristics identified within the study area (Fig. 1). The soil profile in each pit was divided into horizons using the soil description method (FAO, 2006) and a soil type according to the WRB classification was assigned to each soil profile (i.e., 4 in Cambisols, 3 in Calcisols, and 3 in Vertisols). The current and past cultivated layers were assigned to Ap horizons, the well-developed subsoil layers with evident pedological features were assigned to B horizons, and the poorly developed underlying layers with some characteristics similar to parent material were assigned to C horizons as illustrated in Figure 2.

For each horizon, a soil sample was air-dried, well-mixed, and sieved to 2 mm for the measurement of further soil analysis: coarse element, soil texture (i.e. clay, silt and sand content), CEC, exchangeable  $Mg^{2+}$ , and exchangeable  $Ca^{2+}$  content. Soil pH was evaluated using a 1:5 volumetric mixture of dry soil and distilled water (NF ISO 10390 standard). Soil total carbon content (STC) was analyzed by dry combustion via a CHNS elemental analyzer (Thermo Flash2000). SOC content was analyzed, by the same analyzer, after the decarbonation of soil by an acid pretreatment. SIC content was determined by subtracting SOC from STC. All carbon content values (STC, SOC, and SIC) are expressed in  $g.kg^{-1}$ . The quantification of SOC, SIC, or STC contents with a CHNS analyser is subject to an uncertainty of approximately  $0.1 g.kg^{-1}$  (Basile-Doelsch et al., 2023).



**Fig. 2 Illustration of one soil profile for each of the three main soil types considered in this study.**

### 2.3. Topographic metrics

In this study, we tested sixteen topographic indexes which were selected as being the most relevant and frequently used in the literature to explain the distribution of SOC from the plot scale to the catchment scale. They are described in table 1. All these topographic indexes characterized the entire soil profile. They were derived using procedures from the “System for Automated Geoscientific Analysis (SAGA) v. 2.3.1” (see Table 1) from a 4m resolution DEM generated from a stereo pair of panchromatic IKONOS images, which has been filtered twice using a three-kernel low-pass filter to reduce noise from local variations, similar to Li et al. (2018).

**Table 1:** Significance and procedure used for the different topographic indexes tested in this study (1: Basic extraction; 2: Slope, Aspect, Curvature module of SAGA; 3: Topographic openness module of SAGA; 4: LS-factor module of SAGA; 5: Downslope distance gradient module of SAGA; 6: Catchment\_area module of SAGA; 7: Wetness\_index module of SAGA; 8: Stream power index module of SAGA)

Index	Significance	Procedure number
Elevation	Altitude en m	1
L_slope	Local slope in percent. Proxy of runoff velocity	2
Aspect	Azimuth in degree. Proxy of vegetation distribution and soil water balance	2
Pr_curv	Profile curvature (in $m^{-1}$ ), curvature of the surface in the direction of the steepest slope. Proxy of runoff acceleration, soil erosion and deposition rates.	2
Pl_curv	Plan curvature (in $m^{-1}$ ), curvature in a horizontal plane. Proxy of flow divergence and convergence and soil water content	2
G_curv	General curvature (in $m^{-1}$ ), curvature in a horizontal plane. Proxy of soil erosion, runoff velocity, and deposition	2
NOP and POP	Negative and Positive openness, angular measurement of the relationship between surface relief and the horizontal distance. Proxies of soil water content.	3
Up_slope	Upslope slope (m), mean slope of upslope area. Proxy of runoff velocity.	4

LS_factor	Slope-length factor, Proxy of flow convergence and divergence.	4
DI	Downslope index. Proxy of soil water content	5
CA	Catchment area (m <sup>2</sup> ), upstream drainage area. Proxy of runoff velocity and volume.	6
TWI	Topographic wetness index, the ratio between drainage area and local slope. Proxy of soil moisture and sediment deposition.	7
SPI	Stream power index. Proxy of soil erosion and convergence of runoff.	8
C_slope	Catchment slope, modified version of the local slope. Proxy of runoff velocity.	7

## 2.5. Statistics analysis

SOC content spatial variability was first evaluated according to soil types and depth. The difference in SOC content between horizons in cultivated topsoil and horizons in subsoils, and between the different soil types was tested using the parametric “student test” ( $p < 0.05$ ).

The relationships between SOC and topographic indexes, as well as between SOC and soil physico-chemical properties, were then examined using Pearson's correlation coefficient to identify the main driver of SOC content lateral distribution. They were analyzed using the profile as the basis of the analysis ( $n = 10$ ). As the soil physico-chemical properties were measured for each soil horizon, we used equation 1 to derive a mean weighted value by profile for each physico-chemical property. The mean weighted value by profile was evaluated by considering either all the horizons in the profile, the Ap horizons only, or the B+C horizons only, which allowed us to evaluate the possible variations in SOC content factors between topsoils and subsoils.

$$m\_X = \Sigma (X_i * m_i) / \Sigma m_i \quad (\text{eq. 1})$$

*With  $m\_X$ : the mean weighted value of the physico-chemical properties  $X$  for the considered profile;*

*$X_i$ : the value of the physico-chemical properties  $X$  in horizon  $i$ ;  $m_i$ : soil mass of horizon  $i$ .*

The role of physicochemical properties in driving the vertical distribution of SOC content was then investigated in more detail by examining how SOC content correlates with the physicochemical properties of the

soil, using the horizon as the basis for analysis. This was done by including all horizons ( $n = 37$ ) and by subdividing them into cultivated topsoil (*i.e.* Ap horizons,  $n = 16$ ) and subsoils (*i.e.* B and C horizons,  $n = 21$ ).

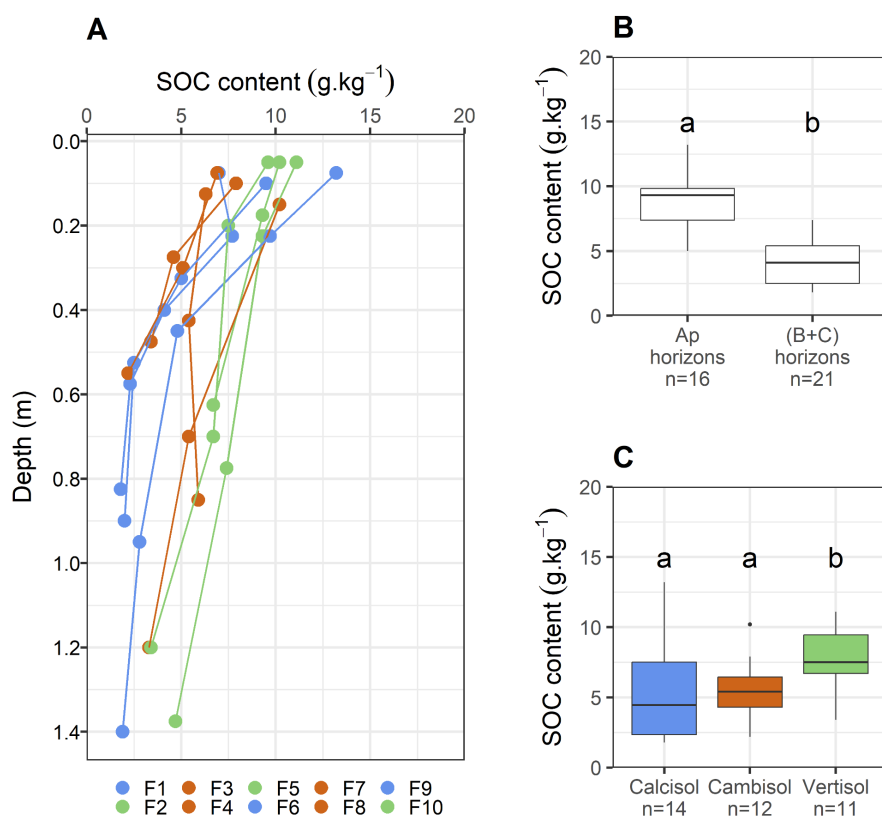
All statistical processing was performed using R software (R core team, 2021) and a set of additional packages including ggplot2, Hmisc, corrplot, dplyr, and cowplot.

### **3. Results**

#### **3.1. Variability of SOC content**

The SOC content in the Kamech catchment varied from 1.8 to 13.2 g.kg<sup>-1</sup>, with a clear pattern of decreasing SOC content with depth ( $r = -0.69$ ;  $p\text{-value} = 0.0269$ ) (Fig. 3A). The results clearly showed significantly higher SOC values ( $p\text{-value} = 4 \cdot 10^{-8}$ ) in the Ap horizons (8.8 g.kg<sup>-1</sup> on average) compared to the B+C horizons (4.1 g.kg<sup>-1</sup> on average) (Fig. 3B). As shown in Figure 3C, significantly higher SOC contents were found in Vertisols (7.8 g.kg<sup>-1</sup> on average) compared to Cambisols (5.6 g.kg<sup>-1</sup>,  $p\text{-value} = 0.027$ ) and Calcisols (5.3 g.kg<sup>-1</sup>,  $p\text{-value} = 0.047$ ).

The average of SOC content in Kamech soils, less than 20 g.kg<sup>-1</sup>, is similar to the SOC values reported in Mediterranean-cultivated soils (Chevallier et al., 2016). These low values can be explained by the low primary production and organic restitution to soils in arid and semi-arid climates (Torrent, 2005).



**Fig. 3 A) Vertical variation in SOC content in the ten soil profiles investigated; B) Comparison of SOC content in topsoil and subsoil; C) Variability of SOC content according to soil type. The Calcisol is represented by the color blue, the Vertisol by green and the Cambisol by brown**

### 3.2. Relationships between SOC, topography and soil physico-chemical properties

The relationships between profile-average SOC, topography and the soil's physicochemical properties were first examined using the profile as a basis for correlation analysis. For that, the matrix of Pearson's correlation coefficients between the mean weighted SOC content ( $m\_SOC$ ), the topographic indexes, and the mean weighted soil physico-chemical properties were evaluated (Table 2). Results showed that  $m\_SOC$  is highly positively correlated with the mean weighted values of clay, exchangeable  $Mg^{2+}$  and CEC (p-value of 0.0042, 0.0095, 0.0077, respectively), and positively correlated with TWI (p-value = 0.0461) when considering all the horizons in the profiles.

Significant correlations between m\_SOC and the previously identified soil physico-chemical properties persisted when subsoil horizons were considered (p-values of 0.0232, 0.0371 and 0.0232 for m\_CEC, m\_Clay and m\_exchMg<sup>2+</sup>, respectively), but disappeared when topsoil horizons were considered.

**Table 2:** Pearson’s correlation coefficients between mean SOC content by soil profile, topographic indexes, and mean soil physico-chemical properties

		m_SOC content (g.kg <sup>-1</sup> )		
		All horizons (n = 10)	Ap horizons (n = 10 )	B+C horizons (n = 10)
Topographic indexes	Elevation	-0.34	0.15	-0.31
	L_slope	0.02	0.01	0.05
	Aspect	-0.23	-0.48	-0.16
	Pr_curv	0.15	0.25	0.01
	Pl_curv	-0.47	-0.52	-0.49
	G_curv	-0.20	-0.21	-0.30
	NOP	0.31	0.19	0.29
	POP	-0.41	-0.07	-0.41
	Up_slope	0.04	-0.18	0.09
	LS_factor	0.24	0.50	0.19
	DI	0.29	0.40	0.23
	CA	0.41	0.50	0.34
	TWI	<b>0.64*</b>	0.48	0.54
	SPI	0.46	0.45	0.42
C_slope	0.06	-0.16	0.12	
Physico-chemical	m_Clay	<b>0.81**</b>	-0.16	<b>0.70*</b>

properties	m_Fine Silt+Clay	<b>0.67*</b>	-0.27	0.60
	m_SIC(g.kg <sup>-1</sup> )	-0.47	0.20	-0.62
	m_pH	-0.06	0.07	-0.25
	m_exchCa <sup>2+</sup>	-0.27	0.23	-0.47
	m_exchMg <sup>2+</sup>	<b>0.77**</b>	-0.15	<b>0.66*</b>
	m_CEC	<b>0.78**</b>	-0.20	<b>0.80**</b>

\* p-value < 0.05; \*\* p-value < 0.01; \*\*\* p-value < 0.001. See Table 1 for a complete description of the topographic indexes. The values in bold are the significant correlation coefficients.

### 3.3. Soil physico-chemical parameters and SOC

The relationships between SOC and the soil's physicochemical properties were then examined using the horizon as a basis for correlation analysis. SOC content exhibited a highly significant negative correlation with pH (p-value < 0.001), and a significant negative correlation with SIC (p-value < 0.05), when all horizons were considered (Table 3). None of the tested physico-chemical properties was significantly correlated with SOC content when considering the Ap horizons only, while CEC and clay content showed a highly (p < 0.01) and moderate (p < 0.05) significant positive correlation with SOC content when considering subsoil horizons.

**Table 3.** Pearson's correlation coefficients between different SOC content and the other soil properties in horizons

	SOC content (g.kg <sup>-1</sup> )		
	All horizons (n = 37)	Ap horizons (n = 16)	B+C Horizons (n = 21)
Clay	0.16	-0.01	<b>0.47*</b>
Fine Silt+Clay	-0.11	-0.10	0.33
SIC (g.kg <sup>-1</sup> )	<b>-0.36*</b>	0.10	-0.37
pH	<b>-0.69***</b>	-0.23	-0.29
exchCa <sup>2+</sup>	0.00	0.26	-0.18
exchMg <sup>2+</sup>	-0.28	-0.04	0.34
CEC	0.14	-0.01	<b>0.60**</b>

\* p-value < 0.05; \*\* p-value < 0.01; \*\*\* p-value < 0.001. The values in bold are the significant correlation coefficients.

#### 4. Discussion

##### 4.1. On the opportunity to disentangle the respective roles of topography and physico-chemical properties

Several studies have shown that, at a small catchment scale, SOC distribution is mainly controlled by LUM, physico-chemical properties and topography (Ramesh et al., 2019; Wiesmeier et al., 2019). The fact that LUM were similar throughout the catchment of the study area provided the opportunity to focus on the role of topography and physicochemical properties on SOC dynamics. In addition, although soil moisture distribution or some physicochemical properties such as soil texture and pH can be influenced by topographic parameters such as slope, elevation and aspect (Moore et al., 1993), no significant correlation was found between topographic indexes and soil physicochemical properties in the studied soil profiles as highlighted in Supplementary data S1. This makes it possible to analyze the respective roles of topographic indexes and physico-chemical properties on SOC distribution by studying each factor separately.

#### **4.2. Factors of lateral SOC distribution**

Our results (Table 2) showed that the mean weighted SOC ( $m\_SOC$ ) in Kamech soil profiles is more correlated with the physico-chemical properties ( $m\_clay$  content,  $m\_Fine\ Silt+Clay$ ,  $m\_CEC$  and  $m\_Mg^{2+}$ ), than with the topographic indexes (only topographic wetness index TWI).

The significant positive correlation between  $m\_SOC$  and the fine soil fraction in the studied soils confirmed the importance of soil texture and soil mineralogy in controlling SOC at the profile scale (Ramesh et al., 2019; Choudhury, 2023). Indeed, many studies have reported that the finest fraction of the soil (i.e.  $< 50\ \mu m$  or  $< 20\ \mu m$ ) contains the highest proportion of SOC, which may explain the higher SOC content in “fine-textured soils than in coarse-textured soils” (Han et al., 2016). This is consistent with the higher SOC values found in this study for Vertisols compared to other soil types, since Vertisol profiles have significantly higher clay content compared to Cambisols and Calcisol profiles (p-value of 0.01 and  $4.94 \cdot 10^{-6}$  respectively). Such variability in SOC among soil types has been documented in many studies at various scales and climatic conditions (Arrouays et al., 2006; Albaladejo et al., 2013). The main explanation in literature of higher SOC content in fine-texture soils is “the high adsorption of SOC to the soil mineral surface” (Basile-Doelsch et al., 2020).

Our results also revealed high positive correlations of profile mean SOC with profile mean CEC ( $m\_CEC$ ) and profile mean exchangeable magnesium content ( $m\_exchMg^{2+}$ ). This finding indicates that the adsorption of SOC by the clay may be favored by other soil physico-chemical properties like polyvalent cations ( $Ca^{2+}$ ;  $Mg^{2+}$ ) as already reported by Ramesh et al. (2019) or Basile-Doelsch et al. (2020). In alkaline calcareous soils, both SOC and clay are negatively charged and there are “high levels of  $Ca^{2+}$  and  $Mg^{2+}$ ” (Wang et al., 2015a). The presence of these polyvalent cations is known to facilitate the adsorption of SOC by clay through cation bridging (Kaiser and Kalbitz, 2012), as well as its stabilization and protection against soil microorganism activity (Wiesmeier et al. 2019, Shabtai et al., 2023). However, this study also revealed that there was no significant correlation between SOC and exchangeable cations when considering the horizon scale (Table 3). This means that either the adsorption of SOC by cationic bridging was not significant in the studied soils, or exchangeable cations were present in such large quantities in our soils that their level in the soils is not significantly affected by the adsorption of SOC by cationic bridging. The high  $exchCa^{2+}$  and  $exchMg^{2+}$  levels observed in our soils (37.4 and 5.5  $cmol+/kg$  in mean, respectively) tend to favor the second option. Finally, the higher SOC content in Vertisol profiles may also be favored by the presence of dense cracks that are open for about 6 months per year (Inoubli et al., 2016), which may act as a delivery pathway for biogenic carbon from the surface to the entire soil profile, including the deep soil horizons.

The role of the topographical position of the soil profiles was found to be weaker than the role of physico-chemical properties in explaining the average SOC content in the studied profiles (Table 2). Indeed, only TWI was significantly positively correlated with the mean value of SOC. TWI is known to be “a good indicator of soil moisture distribution in the landscape” (Li et al., 2018; Wang et al., 2023). The high positive correlation between the SOC content and TWI in the studied soil profiles indicated that SOC content in areas with high TWI is promoted by the presence of wet conditions. An explanation is that higher soil moisture increases the net primary production in the context of a semi-arid climate, favoring SOC input into the soil (Ramesh et al., 2019; Rodrigues et al., 2023). The positive impact of wetter conditions, as a result of hydrological connectivity, on crop production in semi-arid conditions is supported by the recent work of Dhouib et al. (2024) who showed through modelling simulations that above biomass and crop yield on fields receiving runoff from upstream plots can increase by 16% for wheat and 33% for faba beans compared to fields receiving no runoff from upstream plots.

#### **4.3. Factors of vertical SOC distribution**

Our results demonstrated a significant decrease in SOC content with the increase of soil depth across all soil profiles. This finding aligns with the prevalent pattern of vertical distribution of SOC observed in most soils worldwide (Zhao et al., 2016; Balesdent et al., 2018; Shariffar et al., 2019; Choudhury, 2023). The average SOC content in (B+C) horizons was found to be about half of that in Ap horizons, which is in line with previous results in Mediterranean cultivated soils. Indeed, Albaladejo et al. (2013) showed that topsoils are more than twice as rich as subsoils in Spanish cultivated soils. This significant decrease in SOC content with soil depth is generally explained by the decreasing of biogenic carbon inputs in soils with soil depth (Basile-Doelsh et al., 2020), whatever through litter, plant and root residue and their exudates (rhizodeposition). This is especially the case in soils cultivated with annual crops whose root systems explore the soil to a limited depth, as in the studied area. When analyzing the relationship between SOC and clay content in horizons, we found a highly significant correlation in the deep soil horizons (i.e. B+C horizons), while no significant correlation was found in the topsoil cultivated horizons (i.e. Ap horizons). This finding is supported by the literature since SOC content in deep horizons was proved to be highly controlled by clay content in many pedo-climatic contexts (Barré et al., 2017; Choudhury, 2023), whereas SOC in cultivated horizons (Ap) was proved to be driven by several others factors such as crop type and agricultural practices (Hobley et al., 2015; Gray et al., 2015). We also observed that SOC content is better correlated with the clay content (< 20 µm) than with the “Fine silt+clay” content (< 50 µm) in the studied soils, which is in line with the literature review as reported by Wiesmeier et al. (2019). This result confirms the major role of clay content in the

adsorption of SOC to the mineral matrix (Balabane and Plante, 2004) and that the clay fraction is a better indicator of SOC distribution than the fraction of fine silt and clay. Considering all horizons, our results showed that SOC is mainly negatively correlated with pH and SIC. This result may be explained by the vertical distribution of each element. Indeed, pH significantly increased with soil depth ( $r = 0.78$ ,  $p < 0.01$ ) while SOC content significantly decreased with soil depth. The negative correlation between SOC and SIC was significant only when considering all horizons (Table 2). Similar results are reported by Zhao et al. (2016) and Lu et al. (2020) when studying the relationship between SOC and SIC in cultivated calcareous soils in a semi-arid region.

The negative relationship between SOC and SIC found in this study may appear as unexpected when compared to the previous results derived in cultivated calcareous soils in semi-arid regions (Wang et al., 2015b; Sharififar et al., 2023). However, it should be noted that the majority of these previous studies were conducted on irrigated cropland. It is well known that irrigation favors the positive relationship between SOC and SIC by supplying and redistributing  $Mg^{2+}$  and  $Ca^{2+}$  ions in the soil and by stimulating secondary precipitation of SIC due to the interaction between  $Ca^{2+}$  and  $Mg^{2+}$ , which are present in abundance in the soil, the production of  $CO_2$  stimulated by increased microbial activity during periods of wet-dry transition (Ferdush and Paul 2021). Additional research is necessary to enhance our understanding of the relationship between SOC and SIC in calcareous soils cultivated with rainfed crops in semi-arid regions.

#### **4.4. Implications**

This study underlined that clay is the primary factor influencing the distribution of SOC in the studied Mediterranean cultivated catchment. This finding can guide agricultural land management practices to maximise the conservation of the clay fraction and minimise its loss by erosion. For example, reducing soil ploughing helps to preserve soil structure and reduce the destruction of aggregates (Liu et al., 2021; Mancinelli et al., 2023), which reduces the loss of the fine fraction (represented generally by clay) through erosion. The study also highlighted the likely positive role of wetter soil zones on SOC levels. It therefore seems essential to promote soil moisture by, for example, trying to reduce soil water evaporation. All these factors tend to recommend limiting soil erosion and evaporation, which can be done by encouraging permanent ground cover and/or keeping crop residues on the ground after harvesting. To gain a deeper understanding of these interactions and how they affect soil organic carbon (SOC) dynamics in a carbonate basin, further studies are necessary in order to optimize agricultural practice and to enhance soil health and productivity, such as organic amendment.

This local-scale study provides scientific evidence to raise awareness among local stakeholders of the importance of soil and water management for fertility and climate. For future research, it can be a reference for regions in the same environmental context and an example for comparison with other studies with different environmental and climatic contexts.

## 5. Conclusions

This study showed that the average SOC content in the Kamech catchment is in the same range as the SOC content reported in cultivated semi-arid Mediterranean regions, with higher SOC contents in Vertisols than in Cambisols or Calcisols. It also showed that the lateral distribution of SOC is determined more by certain soil physico-chemical properties than by the topographical position within the catchment. The clay fraction of the soil (< 20 µm) appeared to be the property that mainly controlled the lateral and vertical distribution of SOC in the soil, with the exception of the cultivated topsoil horizons in which the SOC content remains very difficult to predict. The role of the topography in SOC distribution has proved to be of secondary importance in this semi-arid context. It appears to manifest mainly in the ability to enhance primary production in areas where runoff water concentrates and accumulates. Finally, this study showed that SOC content was negatively correlated with pH and SIC when considering all the horizons studied. Further studies are needed to better understand the actual interaction between organic and inorganic carbon pools in such a context of calcareous soils cultivated with rainfed crops in a semi-arid context, and in particular the role of abundant polyvalent exchangeable cations ( $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) in this relationship as well as in the adsorption and persistence of SOC on fine minerals.

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