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Research Article

Carbon Storage in Organic, Labile, and Mineral Forms across Irrigated Soils of the Beni Moussa Sub-Perimeter, Tadla Plain (Morocco)

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Abstract
The objective of this study was to evaluate how different soil types —Calcimagnesic , Fersialitic, Cambisol, Hydromorphic, and Isohumic— influence carbon stocks and key physico-chemical properties in semi-arid irrigated agroecosystems of the Beni Moussa perimeter, Morocco. A total of 85 soil samples (0–20 cm depth) were collected during the 2022–2023 dry season and analyzed for physico-chemical characteristics as well as different carbon fractions. Multiple statistical approaches, including analysis of variance (ANOVA), correlation analysis, and principal component analysis (PCA), were applied to assess variations among soil types and identify the main controlling factors. PCA explained 39.7% of the variance, separating carbonate-rich soils from organic-rich soils. ANOVA revealed significant effects of soil type on SOCS, LCS, and SICS, confirming the strong role of pedological differences in carbon dynamics. Isohumic soils, rich in organic matter, stored the highest SOC (≈11.7 kg C m^{-2}) and LC (≈1.2 kg C m^{-2}), while Calcimagnesic and Cambisol soils, with high carbonate content, exhibited elevated SICS (~5.2 kg C m^{-2}). Our results demonstrate that soil type is a determining factor for carbon stocks and fractions. It is therefore essential to adapt agricultural practices to specific soil properties to maximize carbon sequestration potential and promote sustainable management in semi-arid irrigated regions.

Keywords: Morocco, soil carbon stocks, soil types, soil properties, statistical perspective, Tadla plain

1. INTRODUCTION

The intensification of agriculture to meet increasing global food demand poses substantial challenges for sustainable soil management. This is because intensive practices often accelerate soil degradation, nutrient imbalances, and organic matter loss, thereby undermining long-term productivity. Soil quality is central to this issue, as it not only determines crop yields but also regulates biogeochemical cycles and sustains ecosystem health [1]. Over the last six decades, widespread soil degradation has been observed worldwide, driven by population growth, industrial development, and the intensive use of chemical inputs [1]-[4]. These pressures are particularly severe in arid and semi-arid regions, leading to salinization, soil compaction, and depletion of organic matter [5].

Beyond their productive role, soils are key components of the global carbon cycle, acting as either sinks or sources of CO_2 depending on changes in their carbon reserves [6][7]. Carbon sequestration is recognized as an important strategy for mitigating greenhouse gas emissions [8][9] and supporting climate change adaptation [10]. Soils store nearly twice as much carbon as the atmosphere, making them the largest terrestrial reservoir [11]. These stocks are strongly influenced by land use, management practices, and climate [12]. However, total carbon storage alone does not capture the full complexity of soil carbon dynamics; distinguishing between organic, inorganic, and labile carbon fractions provides a better understanding of soil functioning and its sequestration potential. Soil carbon occurs in fractions with contrasting stability and reactivity. Labile carbon is highly sensitive to land-use changes, while total organic carbon underpins fertility, water retention, and structural stability [13][14]. Inorganic (mineral) carbon, often associated with carbonate minerals and clay particles, is more stable over long timescales [15][16]. Understanding the interactions between these fractions and soil physicochemical properties is essential for designing sustainable soil management strategies, particularly in intensively cultivated semi-arid

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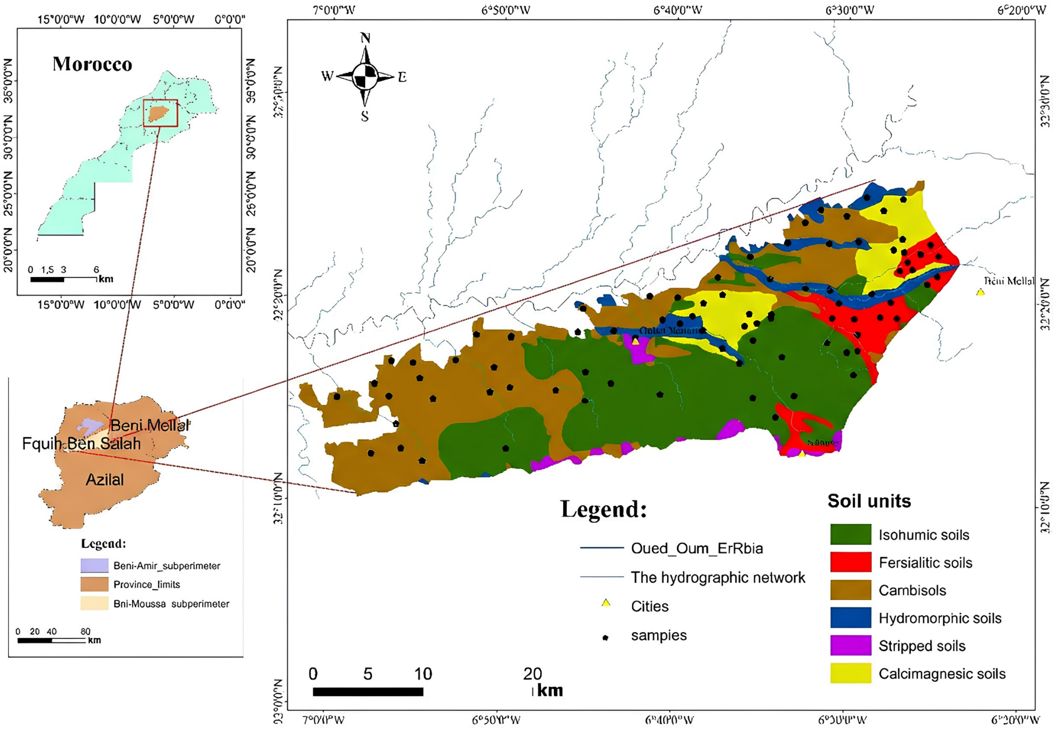


Figure 1. Soil sampling locations in the survey area located in the Tadla plain, Morocco.

regions [17][18].

In Morocco, irrigated agriculture, which plays a central role in the national economy, is often intensive, leading to excessive water consumption, nutritional imbalances, and soil degradation [19]-[21]. The Tadla plain, especially the Beni Moussa irrigated zone, exemplifies these challenges [22]-[25]. While previous studies have examined soil physicochemical characteristics, quality assessment, and trace metal contamination [3][4][23][26], none have compared the dynamics and storage capacity of different carbon forms across multiple soil types in this region. The Beni Moussa area contains a diversity of soils, including Isohumic, subtropical brown, Calcimagnesic, Fersialitic, and Hydromorphic types [10][27]. Isohumic and subtropical brown soils dominate the irrigated zone and possess significant agronomic potential, while Calcimagnesic soils, often located along rivers, are rich in carbonates. Fersialitic soils are marked by strong weathering and high iron oxide content, and Hydromorphic soils, subject to periodic water saturation, show redox-driven carbon dynamics. Comparing these soils can improve our understanding of how physicochemical properties affect carbon storage and help identify the most favorable soils for sequestration in semi-arid agroecosystems.

Previous studies have employed different approaches to investigate soil carbon dynamics. Laboratory analyses of physico-chemical properties such as pH, organic matter, $CaCO_3$, and cation exchange capacity remain fundamental for characterizing soil conditions [28]. Some research has focused on the fractionation of soil organic matter, distinguishing labile and stable pools and applying stability indices such as the Carbon Management Index (CMI) to evaluate carbon dynamics [29]. Statistical tools such as ANOVA have been widely applied to evaluate treatment effects on soil carbon dynamics [30]. In addition, studies have also emphasized the role of local management practices in shaping soil carbon fractions and biological activity [31]. More recently, remote sensing and modeling approaches have been used to predict and map SOC at regional scales. For example, Emadi et al. [32] demonstrated the effectiveness of machine learning algorithms for SOC prediction in Iran, while Bouslihim et al. [33] integrated PRISMA hyperspectral imagery and meta-learning to map SOC in Morocco. In addition, Barakat et al. [34] highlighted the impact of urban land-use change on SOC in Beni Mellal, and Gadal et al. [10] investigated the spatio-temporal links between LULC change and SOC dynamics. Despite these advances, few studies have focused on the comparative assessment of SOC, SIC, and LC fractions across diverse irrigated soil types in Morocco, particularly in the Beni Moussa perimeter. Accordingly, this study aims to characterize the physical and chemical properties of five representative irrigated soil types, assess how these properties influence labile, organic, and inorganic carbon stocks, and determine which soil type has the most significant carbon storage potential. This work is justified by the lack of comparative assessments of carbon fractions across different soil types in the Beni Moussa perimeter. Despite the importance of this irrigated zone for Morocco's agriculture, we hypothesize that soil type strongly controls carbon storage in the Beni-Moussa perimeter, with organic-rich soils favoring SOC and LC accumulation, while carbonate-rich soils act as reservoirs of SIC. These differences are expected to be linked to soil texture, pH, and $CaCO_3$ content.

2. MATERIALS AND METHODS

2.1. Study Area

The study area is located in the Beni Mellal-Khenifra region of Morocco, known for its plentiful water from the Atlas Mountains and fertile land, offering significant agricultural potential [23][35]. This research focused on the Tadla irrigated perimeter (Figure 1), located approximately 200 km southeast of Casablanca. Covering approximately 3,600 km², it is divided by the Oum R'bia River for about 160 km, creating two sub-perimeters with distinct hydraulic features: the Beni Amir in the north (35,600 ha) and Beni Moussa in the south (69,500 ha) [36]. The Tadla plain has a semi-arid continental climate [21], characterized by high temperatures, a roughly five-month rainy season, and annual rainfall averaging 150 to 450 mm, with about 20% year-to-year variation [37]. Geologically, its formations are mainly limestone, marl, and sandstone, dating from the Paleozoic to the Quaternary Periods [38]-[40]. Agriculture employs nearly 62% of the workforce, mainly using plough-based systems. The main products include cereals, legumes, sugar beets, fodder, market gardening, olives, and citrus [41]. Soil quality, essential for agriculture, is threatened by practices such as excessive fertilisation, uncontrolled irrigation, intensive ploughing, and erosion [3][42]. Soil type is a key parameter influencing agricultural soil quality and healthy plant growth [21]. This region is renowned for its variety of soil types and depends heavily on irrigated farming due to its semi -arid climate [1][3][43]. Our study area is characterized by the presence of various soil taxonomy units (ORMVAT, unpublished work). The key units are illustrated in Figure 1.

2.2. Materials

A total of 85 points, spanning five soil types- Calcimagnesic, Fersialitic, Cambisol, Hydromorphic, and Isohumic- were sampled at a depth of 0–20 cm during the end of the dry season

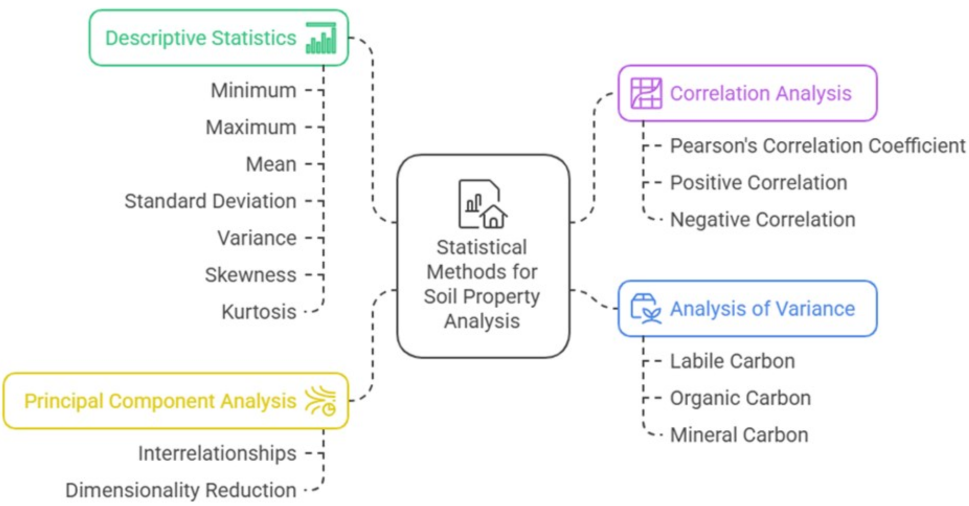


Figure 2. Flowchart of the methodological approach used in this study.

Table 1. Descriptive statistics (mean ± SD) of soil properties across soil types.

Soil Parameters	Calcimagnesic	Fersialitic	Cambisol	Hydromorphic	Isohumic
BD (g/cm^3)	1.287±0.1	1.40±0.13	1.40±0.14	1.38±0.16	1.42±0.12
Stability (%)	66.35±16.72	74.35±14.73	75.03±15.56	75.03±16,81	76.63±15.96
Porosity (%)	52.48±3.94	46.88±5.05	47.03±5.35	47.81±5.94	49.70±7.34
pH-Water	8.07±0.32	7.64±0.36	7.81±0.32	7.00±0.29	7.74±0.38
pH-KCl	6.62±0.48	6.64±0.56	6.77±0.36	6.45±0.41	6.63±0.45
EC (µS/cm)	0.28±0.20	0.13±0.06	0.15±0.01	0.78±0.14	0.21±0.11
OM (%)	4.81±0.84	5.48±1.40	5.41±0.90	6.26±1.12	6.39±1.40
OC (%)	3.47±0.95	3.62±0.71	3.22±0.87	3.36±0.50	4.19±0.66
$CaCO_3$ (%)	19.72±6.28	12.35±3.43	17.57±4.96	9.27±2.78	10.64±3.97
Clay (%)	37.59±6.89	33.17±8.25	29.61±1.94	26.64±9.27	30.61±9.48
Silt (%)	31.72±6.55	32.05±7.76	48.31±2.81	55.47±12.64	53.32±10.93
Sand (%)	30.67±12.20	34.17±6.75	22.07±2.98	18±8.44	16.06±5.91
Sic (%)	2.36±0,75	1.48±0.41	2.10±0.59	1.11 ±0.33	1.27±0.47
Δθ (%)	3.14±1.95	3.67±0.98	5.60±1.87	7.73±4.76	20.19±6.68
SWHC(%)	74.85±11.92	75.41±12.46	84±7.4634	83.52±12.29	71.27±16.12
LC (mg/kg)	356.69±160.29	283.44±95.95	375.83±68.09	335.13±151.03	426.62±111.29
CEC (meq/100 g)	21.83±5.4	19.53±4.44	26.99±7.62	22.15±5.44	22.62±7.92
Ca^{2+} (meq/100 g)	19.45±5.18	14.06±3.65	21.38±4.19	13.92±3.64	17.28±5.34
Mg^{2+}(meq/100 g)	2.10±0.44	1.91±0.25	1.74±0.44	0.26±0.05	1.85±0.73
Na^+ (meq/100 g)	0.50±0.14	0.66±0.14	0.36±0.05	1.78±0.28	0.63±0.23
K^+ (meq/100 g)	0.22±0.05	0.33±0.06	0.21±0.02	0.39±0.10	0.37±0.28

BD: Bulk Density. EC: electrical conductivity. OM: Soil organic matter. OC: Soil organic carbon. $CaCO_3$: Soil carbonate content. SIC: Soil Inorganic Carbon. Δθ : Available Water Content. SWHC: Soil Water Holding Capacity. LC: labile carbon. CEC: Cation exchange capacity. Ca^{2+}: Exchangeable Calcium. Mg^{2+}: Exchangeable Magnesium. Na^+: Exchangeable Sodium. K^+: Exchangeable Potassium.

(September–October 2022–2023). A period chosen to minimize recent agricultural activities and ensure stable soil moisture conditions. This depth was chosen because it corresponds to the main root zone, where nutrient and water uptake are most active and where soil fertility is most directly expressed [44]. The sampling sites were determined based on soil units defined by the Tadla Regional Office for Agricultural Development (ORMVAT).

Laboratory equipment used in this study included a Sension+ MM150 multiparameter meter for measuring pH and electrical conductivity (EC), a Thermolyne muffle furnace for determining organic matter (OM) and calcium carbonate ($CaCO_3$) contents, a flame photometer for measuring sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) concentrations, and a Bernard calcimeter for quantifying soil inorganic carbon. Additional laboratory materials included a 2 mm mesh sieve, a precision balance, 100 cm³ cylinders for bulk density measurement, and standard glassware. Reagents used comprised 1 M potassium chloride (KCl) solution for pH-KCl, 1 M ammonium acetate solution at pH 7 for cation exchange capacity (CEC), and potassium permanganate ($KMnO_4$) for labile carbon measurement. Statistical analyses were performed using RStudio software (version 2024).

2.3. Methods

2.3.1. Soil Sampling and Analysis

After collection, soil samples were air-dried, homogenized, and filtered through a 2 mm sieve. The sampling points, georeferenced, were transformed from WGS84 coordinates to the

Lambert North Morocco system. Subsequently, the soil samples underwent physicochemical analyses as detailed below. The analysed soil parameters included pH, EC, OM, $CaCO_3$, CEC, particle size distribution, and bulk density, as well as complementary physical and chemical properties such as porosity, aggregate stability, soil water holding capacity (SWHC), and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}). These measurements were conducted according to established technical standards and guidelines. Particle size distribution was determined using the Robinson method, following the AFNOR standard NF X31-107 [45]. The bulk density (BD) was calculated using the gravimetric method, by dividing the soil's dry mass at 105 °C by the known soil volume of 100 cm^3 [46], which was then used to calculate porosity. Soil pH was measured in a 1/2.5 soil-to-water suspension after 1 h of equilibration, and pH-KCl was determined in a 1 M KCl solution following the AFNOR X 31-104 standard. Electrical conductivity was measured in a 1/5 soil to water suspension after equilibration. OM was measured after ignition for 4 h at 550 °C, while $CaCO_3$ was determined after 2 h at a specified temperature of 930 °C. The cation exchange capacity was measured by ammonium acetate extraction at pH 7 (Metson method). The concentrations of sodium, potassium, calcium, and magnesium were measured using a flame photometer following extraction with 1 M ammonium acetate at pH 7. The qualitative slake test was used to assess soil aggregate stability. Soil water holding capacity was determined using the percolation method. A known volume of water was poured through a pre-weighed dry soil sample, and the amount of water retained was calculated as the difference between the water added and the water collected.

2.3.2. Calculation of Carbon Stocks

The soil carbon stocks were calculated by multiplying the carbon content by soil bulk density and the thickness of the sampled soil layer (Eq. 1) [47].

$$C^{X}_{stock} = \rho * A * \frac{C^{X}}{100} \quad \textbf{(1)}$$

where $C^{X}stock$ is the carbon stock corresponding to each type of carbon expressed in kg C/m², ρ is the bulk density of the soil (g/cm³), A is the thickness of the soil layer (cm), and C^{X} is the carbon concentration (%). Three forms of carbon were taken into account: organic carbon (x= org), labile carbon (x=lab), and inorganic carbon (x= inorg). Stocks were estimated in the 0–20 cm horizon. Organic carbon (OC) was calculated from

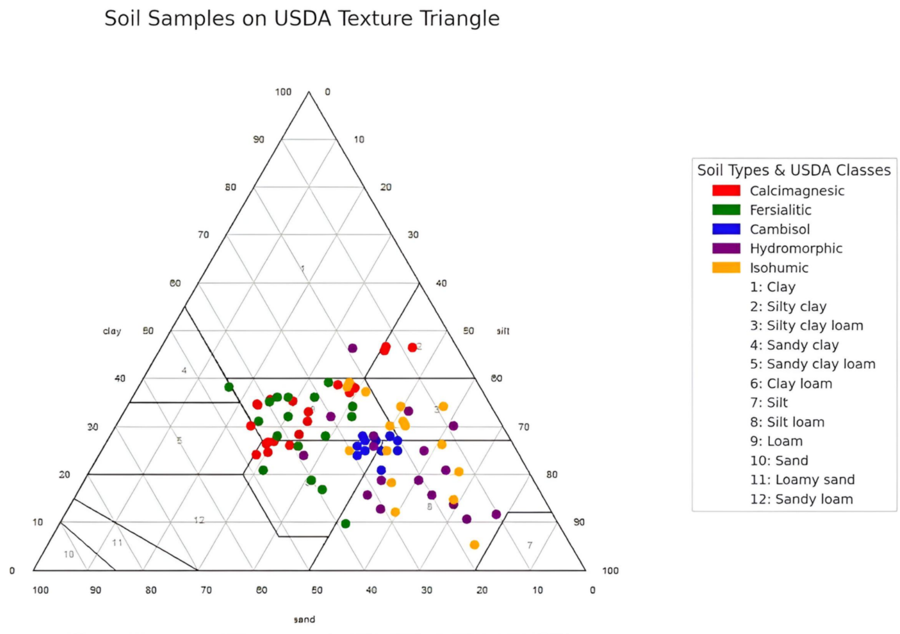


Figure 3. Soil texture classification of irrigated perimeter soils based on the United States Department of Agriculture (USDA) system.

Table 2. The texture class (%) of five soil types in the Beni Moussa area.

Soil Type	Texture Class	Proportion (%)
Calcimagnic	Clay loam	67
	Silty loam	14
	Clay	14
	Clay clay loam	5
Fersialitic	Clay loam	47
	Clay clay loam	18
	Loam	18
	Clay	12
	Silt loam	5
Cambisol	Clay loam	69
	Silty clay loam	23
	Silt loam	8
Hydromorphic	Silt loam	53
	Clay loam	23
	Silty clay loam	18
	Clay	6
Isohumic	Silty clay loam	47
	Silt loam	30
	Clay	12
	Clay loam	6
	Silty clay	5

soil organic matter content measured using a standardised method [48], which was quantified as the mass lost after ignition of the dried soil sample at 550 °C after 4 h in a muffle furnace. Labile carbon was measured by oxidation with potassium permanganate ($KMnO_4$) according to Culman et al. [49]. SIC was quantified using the Bernard calcimeter method.

2.3.3. Statistical Analyses

This study employed various statistical techniques to analyze the variability of physical and chemical properties across five soil types and their influence on carbon storage. An initial descriptive analysis was conducted to determine minimum, maximum, mean, standard deviation, variance, skewness, and kurtosis for all parameters. Pearson's correlation coefficient was used to measure the linear relationships among soil properties. Subsequently, principal component analysis (PCA) was employed to explore the relationships among the variables and to reduce the dataset's complexity. PCA, as a technique for identifying underlying structure, transforms multiple correlated variables into a few independent components [50]. This approach helps identify the key factors affecting soil variability and summarize the relationships among soil constituents [51][52]. Finally, a one-way analysis of variance (ANOVA) was conducted with soil type as the fixed factor to test for significant differences in labile, organic, and inorganic carbon contents. When significant differences were detected, Tukey’s Honest Significant Difference (HSD) test was applied to identify which means differed significantly from each other. The combined application of these statistical methods (descriptive statistics, Pearson correlation, PCA, and ANOVA) (Figure 2) offers an in-depth understanding of soil quality and carbon storage mechanisms across the different soil types examined in the study area.

Table 3. Descriptive statistics for SOC, LCS, and SICS across different soil types.

	Soil type	Min[a]	Max[b]	Mean	SD[c]	Variance	CV[d](%)	Skewness	Kurtosis
SOCS	Calcimagnesic	3.71	12.53	7.55	2.05	4.22	27.19	0.54	3.48
	Fersialitic	6.47	13.87	9.37	1.97	3.89	21.05	0.65	3.01
	Cambisol	4.99	13.21	8.13	2.37	5.64	29.20	0.77	2.89
	Hydromorphic	7.25	11.42	9.12	1.07	1.15	11.77	0.51	2.96
	Isohumic	8.32	15.78	11.69	2.01	4.05	17.22	0.47	2.40
LCS	Calcimagnesic	0.31	1.28	0.76	0.32	0.10	42.40	0.20	1.68
	Fersialitic	0.26	1.33	0.74	0.28	0.08	38.40	0.55	2.59
	Cambisol	0.67	1.39	0.95	0.21	0.04	22.21	0.78	2.91
	Hydromorphic	0.23	1.79	0.92	0.41	0.17	45.38	0.29	2.27
	Isohumic	0.6	1.68	1.19	0.31	0.09	25.8	-0.02	2.22
SICS	Calcimagnesic	2.14	7.77	5.14	1.56	2.45	30.45	-0.21	2.40
	Fersialitic	2.41	6.06	3.82	1.11	1.24	29.10	0.52	2.47
	Cambisol	3.31	8.45	5.28	1.42	2.02	26.88	0.73	2.88
	Hydromorphic	1.98	4.25	3.00	0.78	0.61	26.05	0.30	1.55
	Isohumic	1.70	6.30	3.38	1.35	1.82	39.90	0.39	2.23

SOCS: Soil Organic Carbon stock. LCS: Labile Carbon stock. SICS: Soil Inorganic Carbon Stock

3. RESULTS AND DISCUSSIONS

3.1. Physico-chemical Properties

Descriptive statistics indicated considerable variability in the physicochemical properties of surface horizons across different soil types in the Beni Moussa area (Table 1). Hydromorphic soils exhibited the lowest pH values (pH ≈ 7.0). In contrast, Calcimagnesic soils were clearly alkaline (pH ≈ 8.07), reflecting their high carbonate content and marl-limestone parent material [46]. Such differences in pH are important because acidic conditions in Hydromorphic and Fersialitic soils may restrict microbial activity and slow organic matter decomposition, whereas neutral to alkaline soils (Cambisols and Calcimagnesic) tend to promote higher biological activity and more balanced mineralization [3]. These findings align with recent research in Beni Moussa [20][24][26] and reflect the region's geological makeup- primarily Quaternary marl and limestone deposits covered by red silt, which sustain alkaline conditions across the Tadla plain [41].

Isohumic soil has the highest organic carbon (4.19%), organic matter (6.39%), and labile carbon (426.62 mg/kg), indicating high fertility, as noted by Maissant [40]. In contrast, Fersialitic soil shows moderate OC (3.62%) and OM (5.48%) but the lowest LC (283.44 mg/kg), suggesting more stable organic matter, which partly shapes the physical structure of the soil and, consequently, hydrological processes (erosion, drainage, runoff, and infiltration rates) [53]. Cambisols and Calcimagnesic soils have intermediate OC (3.22–3.48%) and LC (356.69–375.84 mg/kg), reflecting moderate dynamics. Hydromorphic soil has moderate OC (3.37%), high OM (6.26%), and low LC (335.14 mg/kg), linked to poorly decomposed organic matter in anaerobic conditions [26][54]. These findings match El Hamzaoui and El Baghdadi [20], who classified Beni Moussa soils as moderately to highly organic (1.03–5.25%). This variability influences fertility, nutrient retention, and crop suitability [55].

Physical properties also varied considerably. Calcimagnesic soil is characterized by high porosity (52.48%), low bulk density (1.29), and significant $CaCO_3$ content (19.73%), reflecting its aerated structure and alkaline potential linked to parent materials. They also had moderate CEC (~22 meq/100 g) with relatively high Ca^{2+} and Mg^{2+} levels. Cambisols, with lower porosity (~47%) and higher bulk density (~1.4 g cm^{-3}), presented the highest CEC (~27 meq/100 g) and water-holding capacity (~84%), together with balanced base saturation (Ca^{2+}, K^{+}, Mg^{2+}), consistent with their polyhedral structure [40]. Fersialitic soils displayed lower porosity (~47%), reduced CEC (~20 meq/100 g), and moderate $CaCO_3$ (~12%), with low base saturation and elevated Na^{+} (~0.7 meq/100 g), suggesting advanced mineral depletion and nutrient limitations [56]. Hydromorphic soils contained the lowest $CaCO_3$ (~9%) and Ca^{2+} (~14 meq/100 g) but the highest Na^{+} (~1.8 meq/100 g), consistent with salinity problems linked to evaporation and poor drainage [40]. Their high moisture content (~7–8%) and fine silty texture also restricted aeration and

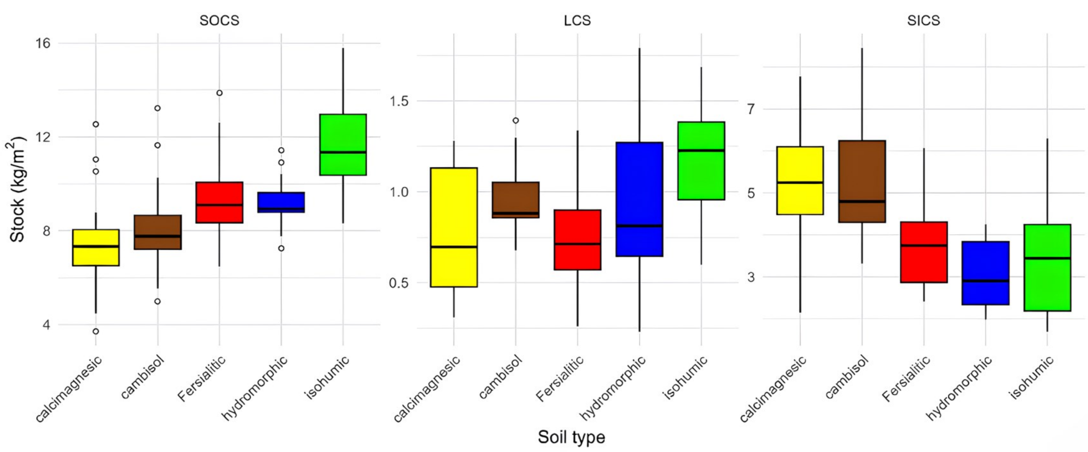
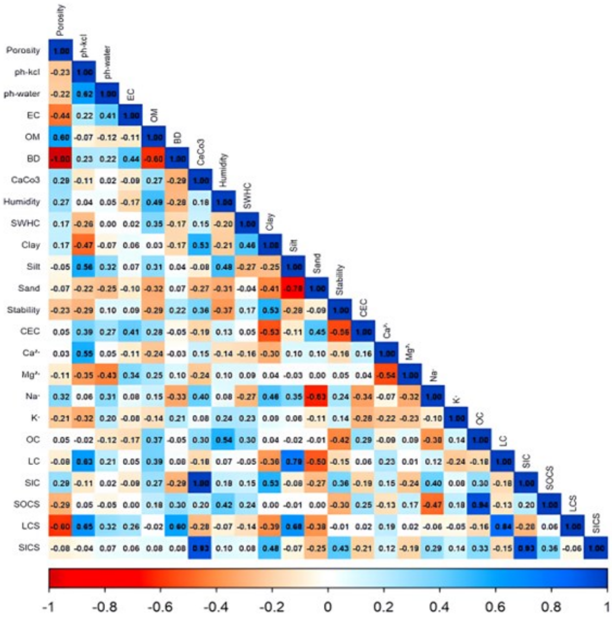


Figure 4. Boxplot representation of organic, labile, and inorganic carbon stocks according to soil type in the Beni Moussa perimeter.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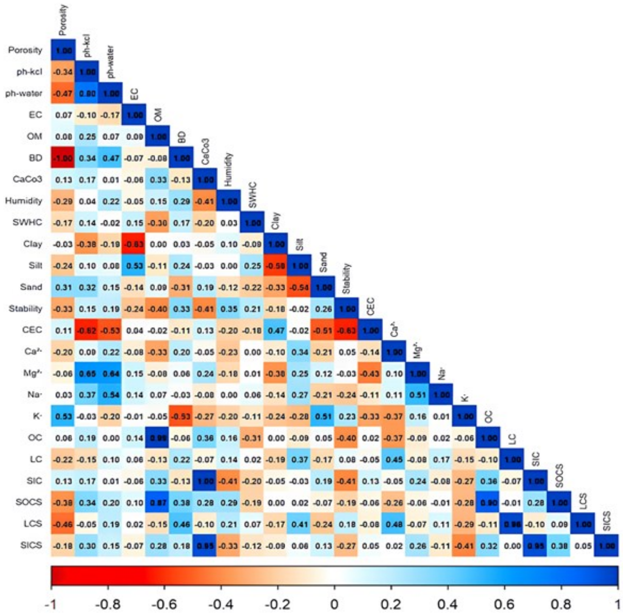
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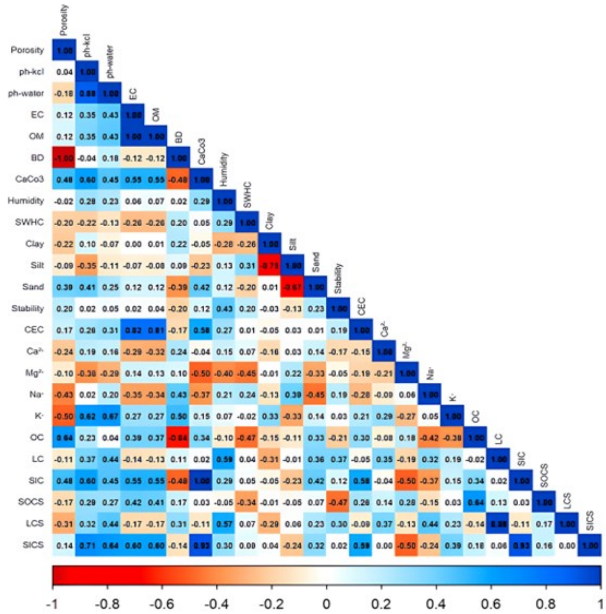
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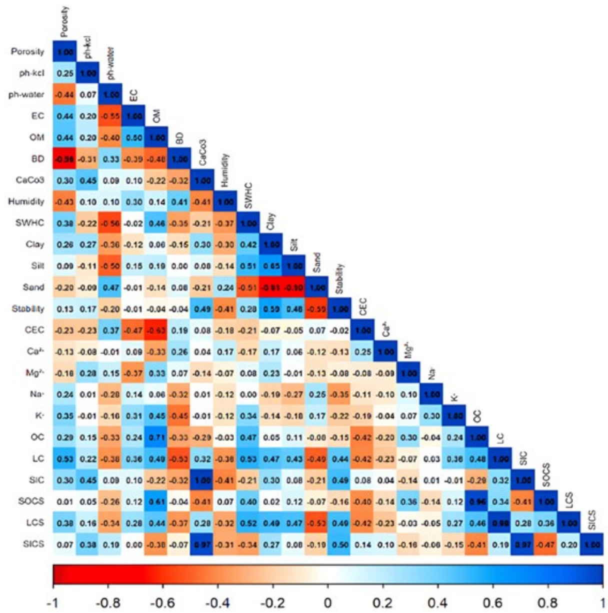
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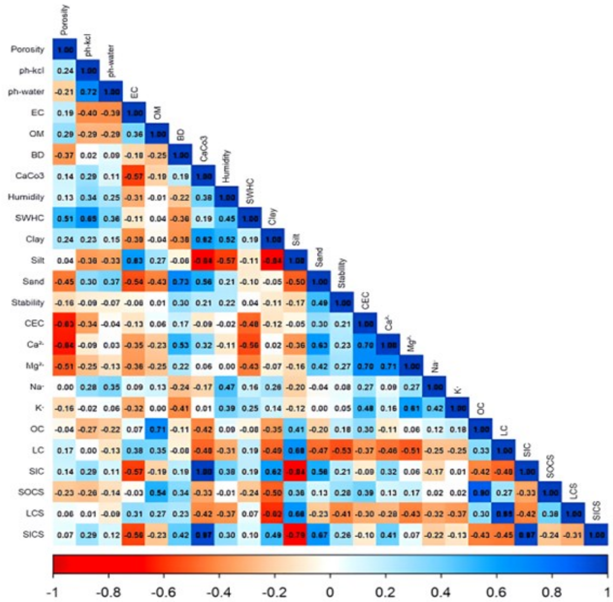

(e)

Figure 5. Pearson correlation between physico-chemical parameters and various forms of carbon for each soil type: (a) Cambisols, (b) Fersialitic, (c) Hydromorphic, (d) Calcimagnesic, and (e) Isohumic soils.

biological activity, explaining the accumulation of organic matter [26]. Isohumic soils presented more balanced properties, with moderate porosity (~50%), notable moisture (~20%), and favorable base saturation (Ca^{2+} ~17, Mg^{2+} ~1.9, Na^{+} ~0.6), supporting soil structure and plant nutrition. Across the five soil types, CEC values ranged from ~13 to 45 meq/100 g, classifying the soils as medium to good [57]. These physical attributes align with recent findings in Beni-Moussa [26][58].

This semi-arid region, highly dependent on irrigated agriculture, is characterized by diverse soil types [1][3][43]. Particle size analysis revealed significant textural differences among the five soil types (Figure 3, Table 2). Calcimagnesic soils were mainly clay loam, showing well-balanced textures that retain water. Fersialitic soils were more varied, containing clay loam, clay, and loam types, which matches advanced weathering and uneven fertility. Cambisols were relatively uniform, with most samples classified as clay loam or silty clay loam, proving their well-structured and fertile nature. Hydromorphic soils were mostly silting loam, indicating poor drainage and aeration that leads to organic matter buildup [26][40]. Isohumic soils were dominated by silty clay loam and silt loam, reflecting fine-textured, biologically active layers with a strong ability to retain organic matter. These texture differences align with earlier classifications of Beni-Moussa soils as loamy clay to clay loam [1] [41].

3.2. Assessment of Soil Carbon Stocks

Table 3 shows the descriptive statistics-minimum, maximum, mean, standard deviation, variance, coefficient of variation, skewness, and kurtosis-for soil organic carbon stock, labile carbon stock, and inorganic carbon stock across various soil types. Figure 4 presents box plots based on the same data, visually illustrating the distribution and variability of these three carbon forms among different soils.

SOC is the largest terrestrial carbon reservoir, and its preservation is essential for global climate balance [59]. Its dynamics are influenced by multiple factors, including climate, organic matter quality, texture, soil type, and management practices such as frequent ploughing, reduced crop rotation, and biomass removal [59]-[61]. Measuring SOC stocks is therefore crucial, as highlighted by Gadal et al. [10], which showed that stocks are greater in forests and natural lands and lower in intensively cultivated areas around Beni Moussa. The highest organic carbon stock is found in Isohumic soils (11.69 kg/m²), mainly due to their high OM content and moderate clay levels, since

OM typically contains about 58% organic carbon [20]. These findings support the results presented by Bernoux et al. [62], which indicated that intermediate soils like Alfisols, similar to Isohumic soils, store more carbon than highly altered Ferralsols, akin to Cambisols, because of soil texture and water retention abilities [63]. Clay helps protect carbon from mineralization by forming stable organo-mineral complexes [64][65]. Fersialitic soils (9.37 kg/m²) and Hydromorphic soils (9.12 kg/m²) follow, due to their fine texture and the physical and chemical protection offered by clay, despite having lower mineral stabilisation capacity. Conversely, Cambisols and Calcimagnesic soils exhibit the lowest stocks (8.14 and 7.55 kg/m²), reflecting their balanced texture, less continuous organic activity, and moderate OM levels that affect soil fertility and stability [41]. These observations confirm that clay-rich soils tend to retain carbon more effectively than loamy soils [66], Cambisols and Calcimagnesic soils, which are less developed and have a balanced texture, show the lowest values, confirming the observations of Barakat et al. [3] on the low organic carbon content of cultivated soils in Beni Moussa due to rapid mineralization and low organic inputs. Barakat et al. [34] also showed that agricultural intensification, which reduced organic inputs, led to a loss of SOC, which is the basis for calculating soil organic carbon, of up to 171.62 kg/m² between 1985 and 2018 in this region. Furthermore, De Mastro et al. [67] specified that SOC stabilisation depends mainly on fine fractions rich in phyllosilicates and amorphous Fe and Al oxides, highlighting the importance of organo-mineral protection. In this context, Darwish and Fadel [61] emphasize that Morocco has climatic conditions and vegetation favorable to carbon accumulation, although intensive agricultural practices limit this potential, such as conventional plowing, which must be replaced by direct seeding (Nt), which significantly increases SOC stocks (+8 to 10%) and stable fractions in clay soils in Morocco's semi-arid climate [68].

Labile carbon, considered to be the fraction of organic carbon readily available for microbial mineralization, is an effective indicator of fertility and sensitivity to changes in agricultural management [69]-[71]. Our results show that Isohumic soils have the highest LCS content (1.18 kg/m²), reflecting their richness in fresh organic matter and their ability to maintain regular inputs of plant residues. This dynamic is consistent with their physical characteristics and good OM-mineral balance, which promotes high biological activity and fertility [40]. Hydromorphic soils follow (0.92 kg/m²), as their water conditions limit the decomposition of organic matter and promote its conservation [72]. Cambisols show intermediate levels (0.95 kg/m²), reflecting their relatively stable but poorly evolved pedological status. In contrast, Fersialitic soils (0.73 kg/m²) and Calcimagnesic (0.76 kg/m²) have the lowest values, probably due to their low initial OM content and a mineralogy less favorable to carbon stabilization. This is consistent with Carrizo et al. [73], who showed that

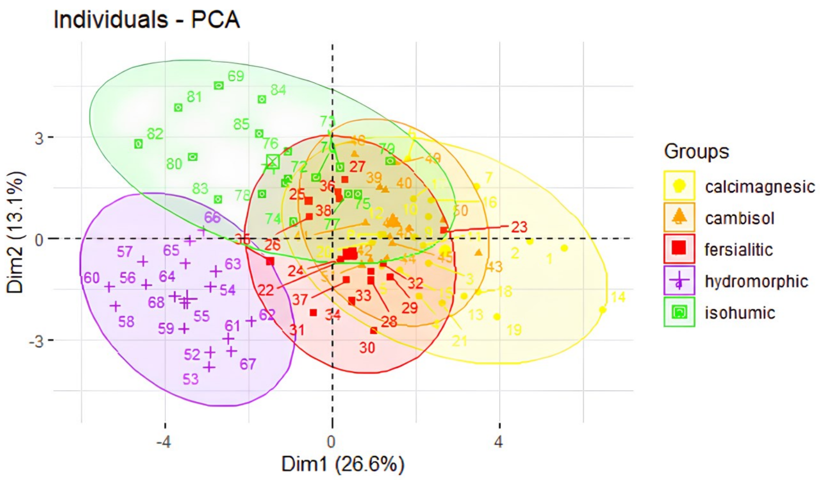

Figure 6. Individual factor map from PCA, showing the contribution of different soil simples through cos^2 values.

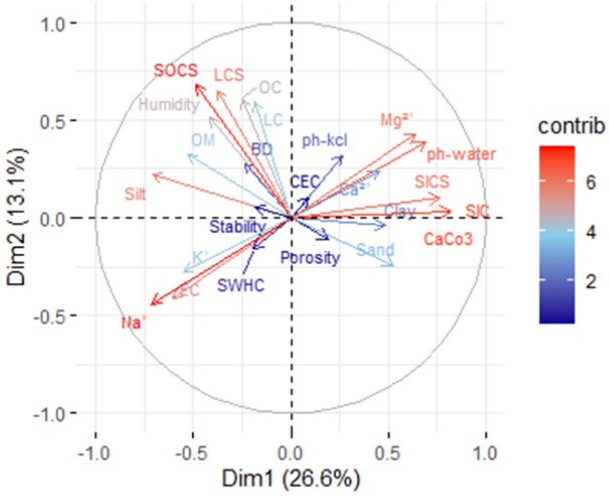

Figure7. Factor map from PCA representing the distribution and relationships among variables.

loamy soils (Argiudoll) are more susceptible to destabilization than loamy-clay soils (Hapludoll). Overall, these results confirm that soils rich in organic matter or subject to hydromorphism play a major role in the dynamics of labile carbon, while mineral or poorly evolved soils require regular organic inputs to improve their biological quality and sequestration potential.

Inorganic carbon in soil plays an essential role in arid and semi-arid soil systems, where it is mainly stored in the form of secondary or lithogenic carbonates. Our results show that Calcimagnesic soils and Cambisols have the highest SICS contents, with respective averages of 5.14 and 5.28 kg/m², linked to their carbonate richness and limited pedogenetic evolution, favoring the accumulation of inorganic forms of carbon and the dominant presence of Quaternary limestone formations [21] [58]. Fersialitic soils show intermediate values (3.83 kg/m²), reflecting their advanced alteration and the lower contribution of primary carbonates. Conversely, Isohumic (3.38 kg/m²) and Hydromorphic (2.99 kg/m²) soils have lower contents, consistent with their dominant organic dynamics and pedological processes favoring the solubilization or leaching of carbonates. These results confirm that SIC, although less dynamic than organic carbon, is a major structural component of the overall carbon reservoir in calcareous and young soils. However, it should be noted that our SICS estimates are limited to the surface layer (0-20 cm) and do not consider the entire soil profile, where deeper horizons can contribute significantly to inorganic carbon storage. Future studies should therefore include deeper layers to provide a more comprehensive assessment of SICS dynamics within the Beni-Moussa perimeter.

3.3. Pearson's Correlation Coefficient

The analysis of Pearson correlations between the different forms of soil carbon in Beni Moussa highlights relationships that are unique to each soil type. In Cambisol soil, a significant positive correlation is observed between LC and SOCS (r = 0.60), as well as between SIC and its stored form (SICS) (r = 0.70) (Figure 5(a)), reflecting the direct contribution of labile fractions to the enhancement of organic stocks and a stable balance of mineral carbon. Similarly, Calcimagnesic soil exhibits marked correlations (LC–SOCS: r = 0.52; SIC–SICS: r = 0.71) (Figure 5(d)), which may be linked to the high carbonate content that promotes the fixation of mineral forms.

Isohumic soil, characterized by its richness in organic matter, also shows strong correlations (LC–SOCS: r = 0.53; SIC–SICS: r = 0.72), confirming the importance of organic inputs in building stable stocks (Figure 5(e)). In Hydromorphic soil, the correlations between LC–SOCS (r = 0.55) and SIC–SICS (r = 0.68) (Figure 5(c)) reflect the effect of reducing conditions associated with water saturation, which limit decomposition and favor carbon accumulation. Finally, Fersialitic soil exhibits notable correlations between LC–SOCS (r = 0.50) and SIC–SICS (r = 0.69) (Figure 5(b)) despite its strong weathering, suggesting that even in highly leached environments, the dynamics of transforming labile carbon into organic stocks and stabilizing mineral carbon remain active. These trends are in line with findings in hot arid regions of India, where SIC stocks averaged 76.71 Mg ha^{-1} in the 0–90 cm profile and showed a significantly positive correlation with SOC ($r = 0.33$, $p < 0.01$), indicating that increases in SOC may lead to enhanced SIC sequestration under certain management conditions [74].

3.4. PCA Result

A PCA was performed on the dataset to explore the relationships between soil types, the different forms of carbon (SOCS, LCS, SICS), and the physico-chemical variables influencing their distribution. The PCA was performed on datasets containing 85 individuals and 24 variables. The first two dimensions (Dim1: 23.9% and Dim2: 13.4%) together explained 39.7% of the total variance, slightly below the conventional 40% threshold. Therefore, Dim3 (9.8%) and Dim4 (9.2%) were also examined (Figure S1), increasing the cumulative variance explained to 58.7% and providing additional insights into soil–carbon relationships. The Dim3–Dim4 plane further supported the separation among soil groups, complementing the trends observed in the Dim1–Dim2 projection in Figure 6.

Dimension 1 (Figure 6) distinguishes Calcimagnesic soils and Cambisols, which are positively correlated with $CaCO_3$, inorganic carbon, pH, and sand content—characteristics typical of poorly developed calcareous soils—from Isohumic and Hydromorphic soils, which are located on the negative side of Dim1 and are associated with higher levels of organic carbon stock, labile carbon stock, organic matter, moisture, and clay (Figure 6) illustrating soils rich in organic carbon and biologically active. Fersialitic soils occupy an intermediate position, reflecting their fine texture and advanced degree of weathering, giving them medium organic storage potential. Dimension 2 (Dim2, Figure 6) further distinguishes Isohumic soils, which are positively associated with organic variables such as SOCS, LCS, and organic matter, from Hydromorphic soils, which are on the negative side of Dim2 and appear to be negatively associated with moisture and sodium (Figure 6). Fersialitic soils, which lie slightly below the horizontal axis, share a similar textural profile to Hydromorphic soils but have a lower water influence, as suggested by their weaker association with moisture-related parameters. Thus, PCA reveals two gradients: (i) a pedological axis between carbonate mineral soils and organic soils (Dim1) and (ii) a hydric and biological axis differentiating soils rich in organic matter (Dim2).

The quality of representation (cos^2 values) further supported these results. For the variables (Figure S2), silt, Na, EC, SICS, K, Mg, pH water, and LCS had high cos^2 values (> 0.5), indicating strong reliability on the Dim1–Dim2 plane. SOCS, LC, organic matter, and humidity showed moderate values (0.3–0.5). In contrast, porosity, clay, sand, Ca^{2+}, $CaCO_3$, SIC, stability, pH KCl, and SWHC exhibited low cos^2 (< 0.3), suggesting limited representation on the first two axes and potential associations with higher-order dimensions. For the individuals (Figure S3), only a few peripheral samples (e.g., 55, 58, 59, 60, 62, 67, 69, 81) reached $cos^2 > 0.5$, while most central samples displayed lower values, indicating reduced reliability of their

Table 4 Results of Wilks' Lambda test for PCA axes (Dim1 and Dim2).

Effect	Wilks' λ	F-value	Num df	Den df	p-value
Soil type	0.059	61.337	8	158	$< 2.2 \times 10^{-16}$

Table 5. One-way ANOVA results for the effect of soil type on soil carbon stocks.

Carbon Stock	Df	Sum of Squares	Mean Square	F-value	p-value
SOCS	4	177.60	44.40	11.93	1.2×10^{-7}
LCS	4	2.282	0.5704	5.531	0.000554
SICS	4	71.60	17.899	10.84	4.51×10^{-7}

Table 6. Tukey HSD post-hoc test results showing significant pairwise differences in carbon stocks between soil types.

Carbon Stock	Soil Type Comparison	Difference	95% CI (Lower–Upper)	p-value	Significance
SOCS	Fersialitic – Calcimagnesic	1.81	0.05–3.57	0.030	*
	Isohumic – Calcimagnesic	4.13	2.38–5.89	<0.0001	***
	Isohumic – Cambisol	3.55	1.57–5.54	<0.0001	***
	Isohumic – Fersialitic	2.32	0.47– 4.16	0.006	**
	Isohumic – Hydromorphic	2.57	0.72–4.41	0.001	**
LCS	Isohumic – Calcimagnesic	0.42	0.13–0.71	0.001	**
	Isohumic – Fersialitic	0.45	0.14–0.75	0.0009	***
SICS	Fersialitic – Calcimagnesic	-1.31	-2.48 – -0.14	0.010	*
	Hydromorphic – Calcimagnesic	-2.14	-3.31 – -0.97	0.00002	***
	Isohumic – Calcimagnesic	-1.75	-2.92 – -0.58	0.0006	***
	Fersialitic – Cambisol	-1.46	-2.78 – -0.13	0.020	*
	Hydromorphic – Cambisol	-2.28	-3.60 – -0.96	0.00006	***
	Isohumic – Cambisol	-1.90	-3.22 – -0.58	0.001	**

projection on the Dim1–Dim2 plane.

PCA also made it possible to meet one of the objectives of this study, which was to identify the parameters most strongly associated with the three forms of carbon in the soils studied. SOCS and LCS are both positively associated with organic matter, moisture, silt and clay content, and structural stability (Figure 7). These correlations reflect the direct influence of organic matter content and fine texture on the accumulation of organic carbon and its labile fractions. Conversely, inorganic carbons stocks are positively associated with pH (water and KCl), sand content, calcium carbonate, magnesium, and electrical conductivity, reflecting alkaline conditions and a more pronounced mineral nature of the soils concerned (Figure 7). In order to complement the PCA and evaluate potential redundancies among variables, Pearson correlation analysis was conducted (Figure 5). It revealed consistent redundancy between LC and SOCS ($r \approx 0.50$–0.60) and between SIC and SICS ($r \approx 0.68$–0.72) across all soil types, while SIC also showed strong correlations with $CaCO_3$ in Calcimagnesic soils. These patterns confirm that some variables convey overlapping information, thereby supporting the decision to emphasize the most contributive variables in the PCA.

This integrated interpretation, supported by cos², contribution, and correlation analyses, demonstrates that carbon fractions and their associated soil parameters are the main drivers of the two identified gradients: a pedological gradient and a hydrological/biological gradient. The first is characterized by soils rich in organic carbon, generally more humid and clay-rich, while the second corresponds to predominantly mineral soils, which are sandier and richer in carbonates. To statistically validate the separation between groups observed in the PCA, a Wilks' Lambda test was applied to the coordinates of the first two principal components (Dim1 and Dim2). The results are summarized in Table 4.

The test shows a highly significant separation between soil groups (Wilks $\lambda = 0.059$; $F = 61.337$; $p < 2.2 \times 10^{-16}$), indicating that the soil type variable substantially explains the organization in the factorial space. This statistical result validates the visual trends observed and confirms the hypotheses of carbon differentiation according to soil type.

3.5. ANOVA of Carbon Stocks According to Soil Type

An analysis of variance was conducted to compare organic carbon stocks, labile carbon stocks, and soil inorganic carbon stocks across five soil types: Calcimagnesic , Cambisol, Fersialitic, Hydromorphic, and Isohumic. The results showed a highly significant impact of soil type on all three-carbon forms: SOCS ($F(4.80) = 11.93$; $p < 0.001$), LCS ($F(4.80) = 5.53$; $p < 0.001$), and SICS ($F(4.80) = 10.84$; $p < 0.001$) (see Table 5). These findings suggest that soil type strongly determines carbon stock variability, supporting the observations made by Zinn et al. [75].

The ANOVA results were supplemented by Tukey's HSD post hoc test, which showed SOCS, LCS, and SICS vary significantly depending on soil type. The results of this test, illustrated in Table 6, reveal significant differences between soil types for the three forms of stored carbon. Regarding soil organic carbon stock, Isohumic soils exhibit significantly higher values than all other soil classifications ($p < 0.0001$), as denoted by letter "a" in Figure 8. Fersialitic and Cambisol soils are categorized within an intermediate group ("b" and "bc"). In contrast, Calcimagnesic soils demonstrate the lowest contents ("c"). Concerning labile carbon, Isohumic soils again demonstrate notably higher values ("a") in comparison to Fersialitic and Calcimagnesic soils ($p < 0.01$). Hydromorphic and Cambisol soils represent an intermediate group ("ab"), indicating less variability between these types. Conversely, in terms of mineral carbon, Calcimagnesic and Cambisol soils possess the highest stocks ("a"), which are significantly greater than those observed in Hydromorphic, Fersialitic, and Isohumic soils (all classified as "b"). These findings confirm that soil type significantly affects the distribution of various carbon forms in soils. Isohumic soils seem to contain the highest levels of organic and labile carbon Stock, whereas Calcimagnesic soils have a greater concentration of mineral carbon. These findings support the PCA and boxplot results, which distinguished different soil groups according to their carbon stocks and physicochemical characteristics.

Our findings support previous research, emphasizing the critical influence of soil type on organic carbon stock variability. Li et al. [76] examined factors affecting soil organic carbon density in Inner Mongolia and found that the significance of various variables depended on land use; in their study, soil type was identified as the key factor, with altitude also playing a role in forest and agricultural areas, while slope had only a minor effect. Similarly, Ayoubi et al [77] observed higher carbon stocks in forest soils than in cultivated soil, attributing this to our ANOVA results, which showed ongoing organic inputs and better structural stability in forests, whereas agricultural practices tend to disturb soil aggregates and accelerate carbon mineralization. These results are consistent with our ANOVA analysis ($p < 0.05$), confirming that soil type is the dominant factor shaping organic carbon stocks across the study area. Overall, the results of the various statistical methods used show that soil type is a determining factor in carbon dynamics in the Beni-Moussa area. Isohumic soils, with their fine texture and high organic matter content, favour the storage of SOC and LC, while carbonate-rich soils, such as Calcimagnesic soils and Cambisols,

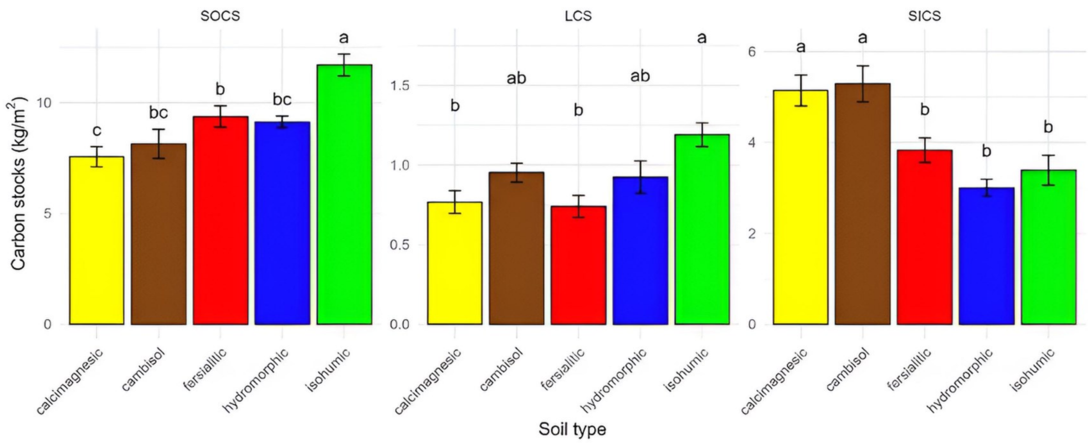

Figure 8. Average stocks of organic, labile, and inorganic carbon by soil type (kg C/m²), with standard deviation and Tukey's comparison letters (homogeneous groups).

are the main reservoirs of SIC. This highlights the importance of taking soil type into account when designing carbon management and sequestration strategies in irrigated semi-arid agroecosystems.

4. CONCLUSIONS

This work evaluated the storage potential of three types of carbon (organic, labile, and inorganic) in five soils types (Calcimagnesic , Fersialitic, Cambisol, Hydromorphic, and Isohumic) and their relationship with the physico-chemical properties of the soils in the Tadla plain, Morocco. A total of 85 samples (0–20 cm) were analyzed using laboratory measurements combined with PCA, ANOVA, and correlation analysis. The results highlight the strong influence of soil type on both stocks and physico-chemical properties in the Beni Moussa perimeter. Isohumic soils, rich in organic matter, stored the highest SOC and LC, whereas Calcimagnesic and Cambisol soils, with high carbonate content, were the main reservoirs of SIC. Hydromorphic soils accumulated organic matter under poor drainage but were constrained by salinity, while Fersialitic soils showed reduced fertility and low LC. These results highlight the importance of integrating specific soil properties into sustainable land management strategies. In particular, maintaining organic inputs in Isohumic soils can improve SOC and LC storage, while improving drainage and controlling salinity in Hydromorphic soils could mitigate fertility losses. For Calcimagnesic and Cambisols, monitoring carbonate dynamics is essential to better account for SIC stocks. Future research should prioritize long-term monitoring of soil carbon fractions, the use of modeling approaches to predict sequestration potential under different scenarios, and the adaptation of irrigation and fertilization practices to local soil conditions.

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Conflicts of Interest

The authors declare no conflict of interest.

SUPPORTING INFORMATION

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DECLARATION OF GENERATIVE AI

While preparing this work, the author(s) used ChatGPT (OpenAI) exclusively for language editing and grammar checks to enhance clarity and readability. The tool was not employed to create or alter scientific content, data, analyses, or conclusions. After utilizing the tool, the author(s) reviewed and made necessary edits and are fully responsible for the final content of the publication.

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