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Spatial Assessment of Soil Degradation in the Western Cotton-Growing Zone of Burkina Faso

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Abstract

This study assesses the extent of soil degradation in the western cotton-farming region of Burkina Faso, aiming to provide essential insights to support sustainable land management efforts and to guide future research on soil fertility restoration strategies. A total of 32 soil samples were collected along a transect designed according to the physiographic units and land use: protected forests, croplands, and pasturelands. Soil physico-chemical analyses were conducted to determine Organic Matter content (OM), Cation Exchange Capacity (CEC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), acidity (pH_{H2O}) and soil texture. Spatial distribution of these parameters was mapped using the Inverse Distance Weighted (IDW) interpolation method. Additionally, soil degradation was assessed with a synthetic Soil Degradation Index (SDI). The impact of land use patterns and topography on soil fertility was analysed through the SDI and linear regression, respectively. Results indicate that over 95% of soils had OM levels below 2% and CEC values were predominantly low to very low. Moreover, more than 55% of soils were strongly acidic and nutrient levels were low in over 70% of soils. Soil texture was dominated by sandy fractions, ranging from 27% to 80%, showing a positive correlation with slope. In ferruginous soils located on steep slopes, degradation levels ranged from moderate (81% of the soils) to severe (19%). In croplands and pasturelands, key soil parameters, such as C, N, K and CEC, were approximately 20% lower than in forest lands, although there was a slight increase in sand and P content. This finding highlights the alarming degradation of soil under agricultural and grazing pressure and emphasizes the urgent need for sustainable soil fertility management strategies to preserve and enhance soil productivity.

Keywords

Spatial Analysis, Soil Degradation, Soil Fertility, Cotton-Growing Area, Land Use Patterns

1. Introduction

Soil fertility, defined by its physical, chemical, and biological properties, has a direct impact on crops productivity. Alarmingly, the soil fertility decline has become a major worldwide issue, posing significant challenges, especially in regions such as sub-Saharan Africa [1], where the economy and the livelihoods of the local population are heavily dependent on agriculture [2]. In sub-Saharan Africa, the poor intrinsic properties of the soils combined with the harsh climatic conditions and the inadequate agricultural practices led to an annual loss of approximately 50 kg ha^{-1} of nutrients [3] [4] and a loss of about 50 tons of organic carbon (OC) after three decades of continuous cropping [5]. This ongoing degradation impacts more than 20% of agricultural lands and compromises the food security of over 65% of the population [6].

In Burkina Faso, specifically, soil degradation affects more than 30% of the land, with particularly severe degradation in areas of intensive cotton production [7] [8]. The expansion of cotton cultivation primarily occurs through the conversion of woodlands into cropland and the suppression of fallow land [9]. The corollary effects of this land use change, combined with mechanized ploughing, include increased exposure of soils to degradation factors, a continuous decline of their fertility [5] and indirectly, a reduction of crops yields and a fragilization of living standards in the country [10].

Particularly, the soil fertility management in the cotton-based farming systems of Burkina Faso, and especially in the Western cotton farming areas, is mainly based on the application of mineral fertilizers. However, this has been proved insufficient to compensate for nutrients losses due to crop exports [11]. Moreover, intensive conventional ploughing methods used, although contributing to reduce labour, led to soil depletion in clay and nutrients [12] [13]. Nutrients losses reported by previous studies on cotton-based farming systems highlight persistent soil degradation and the resulting decline in soil fertility, which poses a serious threat to sustainable agricultural production and farmers' resilience. However, the lack of comprehensive information on the current baseline status of soil degradation in these regions represents a significant knowledge gap that hinders the identification and adoption of tailored sustainable soil management strategies. In this context, a comprehensive baseline assessment of soil degradation, considering spatial variability, is essential to provide crucial insights needed to identify suitable technological packages and management practices that can sustainably improve soil fertility [6] [14].

Building on the hypothesis that excessive land pressure and inadequate soil management have significantly impacted soil fertility in the western cotton-growing area of Burkina Faso, the present study aims to establish a detailed baseline of soil degradation status of this area, focusing on the spatial distribution of key soil fertility indicators across different topographic and land-use contexts. Ultimately, the goal is to inform the identification of locally suitable and effective soil fertility management strategies that support sustainable agricultural production and resilience among farmers in this region.

2. Materials and Methods

2.1. Study Area

The study was conducted in the western cotton-growing area of Burkina Faso, specifically in the villages of Béréba, Dohoun, Wakui, and Sara in the Tuy province, as well as Bondokui in the Mouhoun province (**Figure 1**). The study area lies within the Sudanian and Sudano-Sahelian climatic zones (**Figure 1**), experiencing a range of annual rainfall from approximately 600 to 1200 mm. The annual aridity index (rainfall/reference evapotranspiration) varies from 0.43 to 0.49, classifying it as a semi-arid region (1994-2023, NASA POWER data). Average monthly temperatures vary modestly throughout the year, typically falling between 25˚C and 33˚C, with peak maximum temperatures reaching up to 40˚C during the hottest months of March and April. Rainfall is highly seasonal, concentrated in a single wet season from May to October, accounting for more of 90% of the annual total. The dry season, spanning from November to April, has minimal to no rainfall (**Figure 2**). The vegetation is primarily composed of shrubby and arboreal savannah. The regional farming system is characterized by smallholder agriculture. Traditional fallow periods have been significantly reduced due to increasing land pressure, contributing to the observed soil degradation patterns. Agricultural lands, long dedicated to cotton and rotation crops cultivation, have suffered from inadequate integrated soil fertility management (**Figure 3**). As a result, soil degradation has become a pervasive issue leading to declining yield [11].

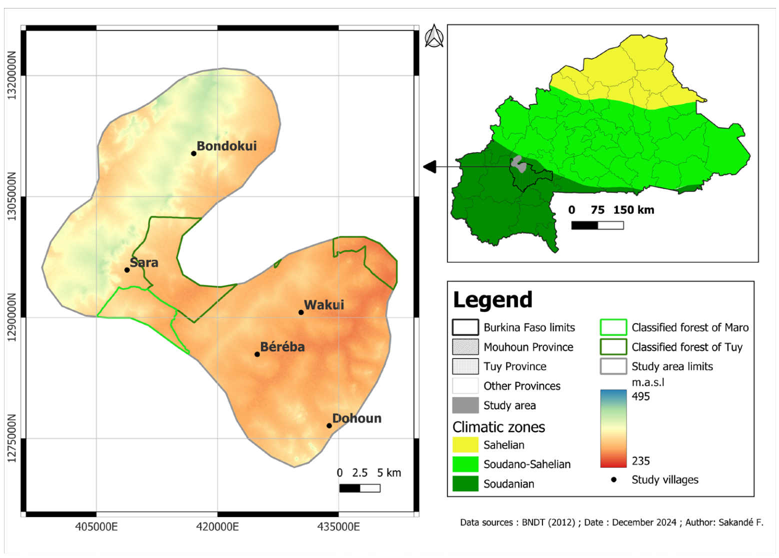

Figure 1. Map of the study area in western Burkina Faso, showing the villages of Bondokui, Sara, Wakui, Béréba, and Dohoun within the Mouhoun and Tuy provinces.

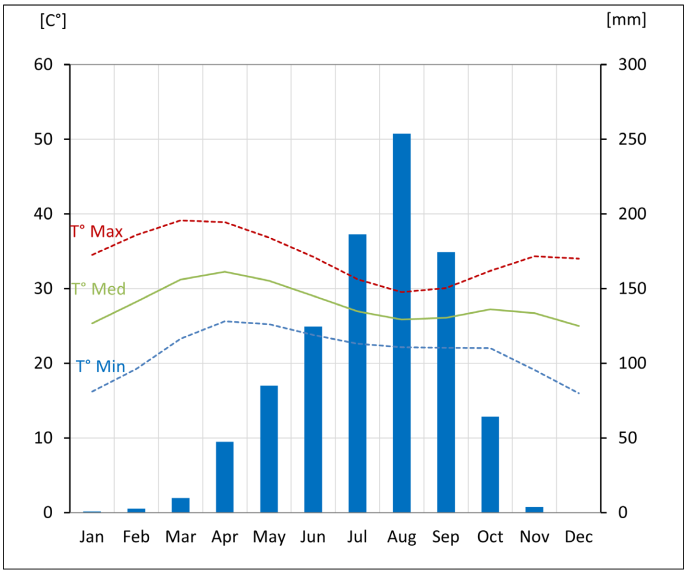

Figure 2. Thermo-pluviometric diagram representing the climatic trends (1994-2023) of the study area. Data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.

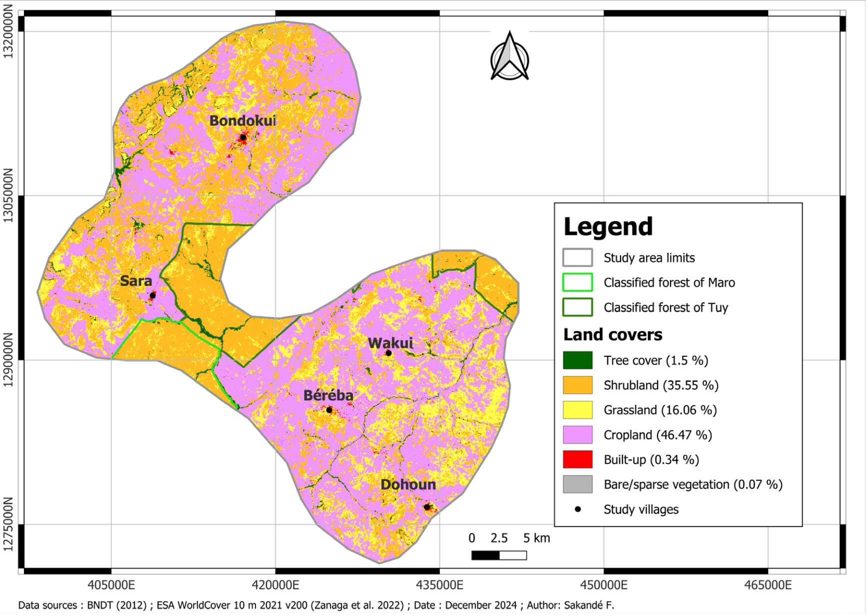

Figure 3. Land cover of the study area.

2.2. Sampling and Data Collection

The soil sampling method, following the recommendations of Brabant [14] was based on physiographic units defined by soil types and geomorphology. Seven physiographic units were identified for data collection (**Figure 3**). Sampling was conducted using the free-soil survey method (which involves selecting sampling sites based on representative landscape features rather than a rigid grid) during [15] the dry season (January-April), with sampling points selected according to the physiographic units and main land use patterns (classified forests, croplands and pasturelands). The classified forests described in this study are protected areas where all agricultural and grazing activities are prohibited by law. Pasturelands consist of natural grasslands and shrublands used for extensive grazing of cattle, sheep, and goats. Croplands in the study area are primarily managed under cotton-cereal rotation systems, with cotton as the main cash crop alternating with cereals (maize, sorghum, millet). Farming practices include intensive conventional ploughing using animal traction or mechanized equipment. In total, 32 data collection points were identified (**Figure 4**). Composite soil sample at each sampled point was then collected at a depth of 0 - 30 cm to determine their physical and chemical parameters.

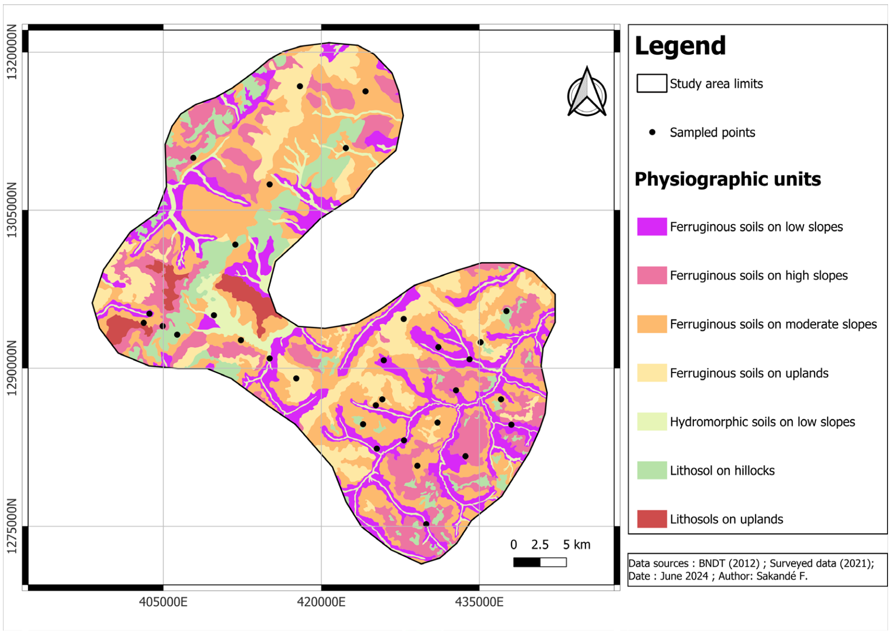

Figure 4. Physiographic map of the study area in western Burkina Faso, displaying the distribution of soil types across various slopes and landscape features.

2.3. Physico-Chemical Analysis and Soil Fertility Assessment Sampling and Data Collection

The collected soil samples were air-dried and sieved to 2 mm and 0.5 mm for analyses. Soil texture was assessed using the three-fraction granulometry method (sand, silt and clay), following the international method adapted to the Robinson pipette. OC was measured using the Walkley and Black [16] method and from this, the OM content was calculated (OM = C * 1.72). The soil acidity (pH_{H2O}) was determined by direct reading using a pH meter in soil solution dissolved at soil: water ratio of 1:2.5, in accordance with the AFNOR NF X-31-103 standard [17]. Total nitrogen (N) was determined by the Kjeldahl (1883) [18] method, and available phosphorus (P) was extracted and measured following the Bray and Kurtz [19] method. Available potassium (K) was extracted with sulfuric acid and measured directly using a flame photometer. Finally, the CEC was measured from a solution of the exchangeable bases.

Soil fertility status was assessed according to standards established by the National Soil Office of Burkina Faso [20], as outlined in **Table 1**.

Table 1. Standard for the interpretation of soil fertility in Burkina Faso [20].

Parameters		Parameter class				
		Very low	Low	Medium	High	Very high
OM	%	<0.5	0.5 - 1.0	1.0 - 2.0	2.0 - 3.0	>3.0
	individual quotation*	1	2	3	4	5
Total N	%	<0.02	0.02 - 0.06	0.06 - 0.10	0.10 - 0.14	>0.14
	individual quotation	2	2.5	3	3.5	4
P	mg/kg	<5	5 - 10	10 - 20	20 - 30	>30
	individual quotation	2	2.5	3	3.5	4
K	mg/kg	<25	25 - 50	50 - 100	100 - 200	>200
	individual quotation	2	2.5	3	3.5	4
CEC	$Cmol^{+} kg^{-1}$	<5	5 - 10	10 - 15	15 - 20	>20
	individual quotation	2	2.5	3	3.5	4
pH (H_2O)	-	>9.0 <4.5	8.5 - 9.0 4.6 - 5.0	7.9 - 8.4 5.1 - 5.5	7.4 - 7.8 5.6 - 6.0	6.1 - 7.3
	individual quotation	1	2	3	4	5
Sum of quotations		<20.9	21.0 - 26.9	27.0 - 32.9	33.0 - 38.9	>39.0
Soil fertility classes		Very low	Low	Medium	High	Very high

OM: Organic matter; CEC: Cation Exchange Capacity; N: Nitrogen; P: Available phosphorus; K: Available Potassium. * Weight of each element in the formation of final soil fertility.

2.4. Data Analysis

Statistical analyses and graph design were performed using R software version 4.3 [21] while QGIS software version 3.28 [22] was used for geospatial analyses and mapzztial distribution of chemical elements and soil texture using the Inverse Distance Weighted (IDW) interpolation method [23]-[25]. The IDW method is widely used to predict soil fertility, generating effective maps for estimating soil fertility at unsampled locations within each area [26] [27]. Spatial analysis was combined with linear regression to examine the relationship between soil physico-chemical parameters and altitude, a descriptor of topography, with a significance threshold set at 5%.

To assess the state of soil degradation, the method of Brabant [14] was adopted (**Table 2**). This method is based on a synthetic index obtained by combining the extension classes and soil fertility classes of each physiographic unit. Chemical fertility standards [20], reported in **Table 1**, were used to assess the extent of the contribution of each chemical element. Finally, the influence of land use patterns on soil degradation was examined using the Soil Degradation Index (SDI), with protected forests (uncultivated areas) serving as a reference. The SDI is generally used to evaluate the impact of land use on soil properties ([28] [29]. In this study, SDI was calculated using the Equation (1):

$$SDI = \left(\frac{X_a - X_b}{X_b} \right) * 100$$

where X_a represents the value of the soil parameter considered for crop land or pastureland, and X_b is the corresponding value for the protected forests.

Table 2. Refined synthetic index of soil degradation [14]. The degradation level is classified into five categories (Very Low, Low, Medium, High, Very High) based on two main criteria: the percentage extension of degraded land and the soil's chemical fertility level. The index column represents the degradation index. The "Extension + degree" column provides a combined degradation score that synthesizes the extent and severity of degradation, with higher values indicating more severe soil degradation.

Degradation levels	Class	Extension	Soil chemical of fertility level	Index	Extension + degree
Very Low	1	<5	>39.0	1	2
Low	2	5 - 25	33.0 - 38.9	2	3 - 4
Medium	3	26 - 50	27.0 - 32.9	3	5 - 6
High	4	51 - 75	21.0 - 26.9	4	7 - 8
Very high	5	>75	<20.9	5	9 - 10

3. Results

3.1. Spatial Distribution of Soil Physico-Chemical Parameters

The spatial distribution of chemical parameters indicates that the OM contents of over 95% of the soils in the study area was less than 2% (**Figure 5** and **Table 2**). The CEC of most soils ranged from very low (53.9% of the area) to low (43.7%) (**Figure 4** and **Table 3**). The pH_{H2O} values of soils ranged from 4.5 to 7.2, with the majority of soils being strongly acidic (55.1%) to moderately acidic (37.7%) (**Figure 5** and **Table 3**). Total N contents varied between 0.02% and 0.12% (**Figure 5**), with more than 75% of soils in the study area falling into the low N class (**Table 3**). The soils also showed poor levels of assimilable phosphorus (P), with values ranging from 0.7 to 13.4 mg kg^{-1}. However, about 70% of soils had medium levels of available potassium (K).

Concerning soil particles size distribution, the area is characterized by a proportion of 20.55% clay soil, 26.08% silty soil and 53.37% sandy soil. The sand content ranged from 27% to 80% is the highest and is about twice the silt and clay content (**Figure 6**).

Two soil physical parameters (sand and clay) were significantly influenced by altitude, which characterizes the topography of the study area. Although a negative trend was observed for the silt fraction ($R = -0.17$) it was not statistically significant. Concerning soil chemical parameters (**Figure 7**, **Table 4**), no significant relationship was observed between their content and altitude. Additionally, only sand

and clay contents were significantly influenced by the topography characterized by altitude (Figure 6, Table 4). Linear regression analysis indicates that sand content is positively correlated with altitude (R = +0.38; p-value = 0.03) (Table 4), whereas the correlation between clay content and altitude is negative (R = −0.41; p-value = 0.02) (Table 4).

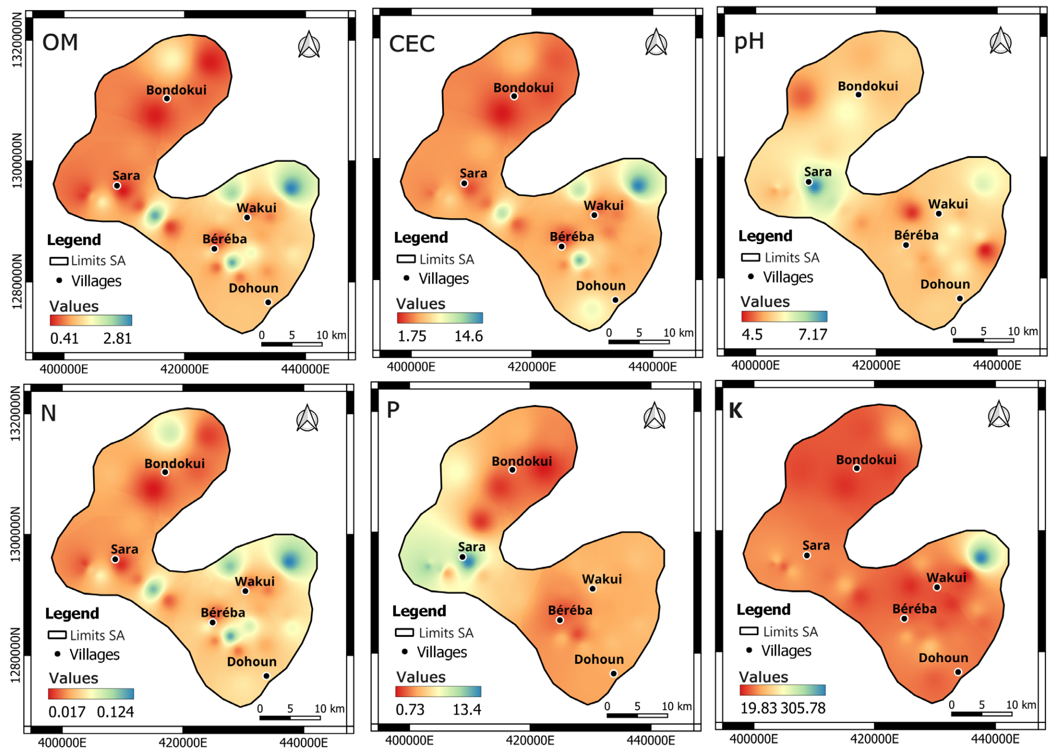

Figure 5. Spatial distribution maps of soil properties across the study area in western Burkina Faso, displayed for six key indicators: Organic Matter % (OM), Cation Exchange Capacity in cmol/kg (CEC), pH (H_2O), nitrogen % (N), phosphorus in mg/kg (P) and potassium in mg/kg (K). Each map presents interpolated values with colour gradients, where red indicates lower values and blue higher values, as per the scale bar in each panel.

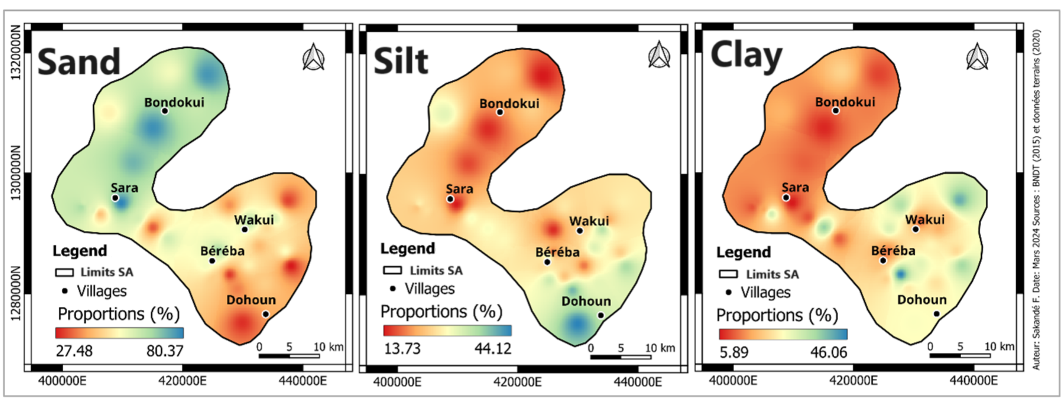

Figure 6. Spatial distribution of soil texture components (sand, silt, and clay) across the study area (SA) in western Burkina Faso. Each map shows the interpolated proportion (%) of sand, silt, and clay, with colour gradients representing relative concentrations (from low to high, as indicated by the scale bars in each panel).

Table 3. Size and proportion of the areas in the different soil fertility categories for the soil chemical parameters in the western cotton-growing zone of Burkina Faso.

Chemical parameters	Very Low		Weak		Medium		High		Very high	
	Sup (ha)	Prop (%)	Sup (ha)	Prop (%)	Sup (ha)	Prop (%)	Sup (ha)	Prop (%)	Sup (ha)	Prop (%)
OM (%)	1232.7	1.19	46737.2	45.19	52431.1	50.70	3021.5	2.92	0.0	0.00
CEC (cmol/kg)	55783.1	53.94	45232.7	43.74	2406.7	2.33	0.0	0.00	0.0	0.00
pH_{H2O}	0.0	0.00	3132.7	3.03	56981.8	55.10	38961.1	37.67	4346.9	4.20
N (%)	364.6	0.35	79346.4	76.72	22420.2	21.68	1291.4	1.25	0.0	0.00
P (mg/kg)	76921.2	74.38	25522.0	24.68	979.4	0.95	0.0	0.00	0.0	0.00
K (mg/kg)	55.6	0.05	24205.9	23.40	73223.1	70.80	4553.9	4.40	1384.1	1.34

OM: Organic matter; CEC: Cation Exchange Capacity; N: Nitrogen; P: Available phosphorus; K: Available Potassium; Sup: Area size; Prop: Area proportion.

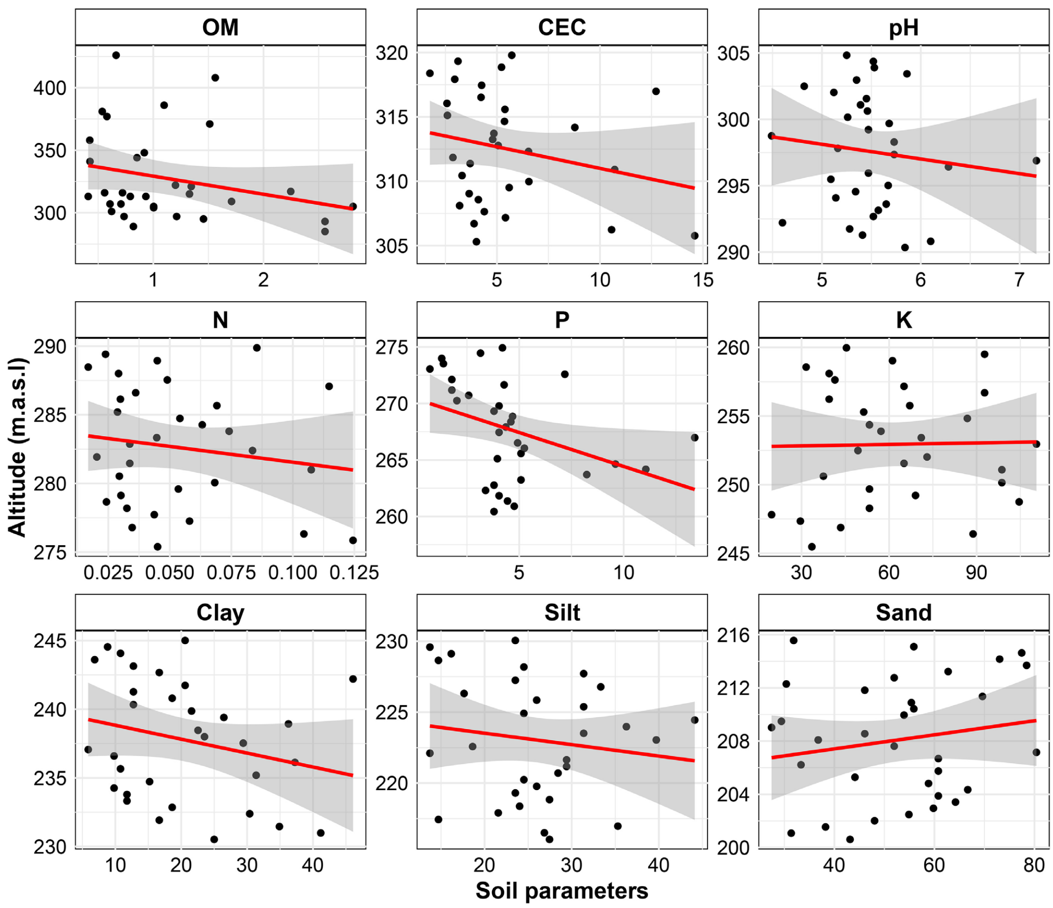

Figure 7. Scatter plots showing the relationship between altitude (m.a.s.l.) and various soil parameters across the study area. Each plot represents a different soil parameter, including Organic Matter % (OM), Cation Exchange Capacity in $cmol^{+}$ kg^{-1} (CEC), pH (H_2O), nitrogen % (N), phosphorus in mg kg^{-1} (P), potassium in mg kg^{-1} (K) and clay, silt, and sand (%). The red lines indicate linear regression trends, with shaded grey areas representing the 95% confidence intervals.

Table 4. Linear regression between Altitude and soil physico-chemical parameters.

Parameters	R	p-value	Significance
OM (%)	−0.26	0.150	NS
CEC (cmol⁺ kg⁻¹)	−0.22	0.221	NS
pH_{H2O}	+0.14	0.449	NS
N (%)	−0.20	0.272	NS
P (mg kg⁻¹)	+0.29	0.107	NS
K (mg kg⁻¹)	−0.06	0.726	NS
Clay (%)	−0.41	0.020	S
Silt (%)	−0.17	0.351	NS
Sand (%)	+0.38	0.031	S

OM: Organic matter; CEC: Cation Exchange Capacity; N: Nitrogen; P: Available phosphorus; K: Available Potassium; R: correlation coefficient; NS: Not significant; S: Significant.

3.2. Soil Degradation Status in the Study Area

The results of our analyses indicate that the intensity of soil degradation within the study area varies across physiographic units (Figure 8). Degradation was generally moderate in most units, affecting approximately 81% of the study area. However, in ferruginous soils on steep slopes, degradation was high, impacting about 19% of the area (Figure 8).

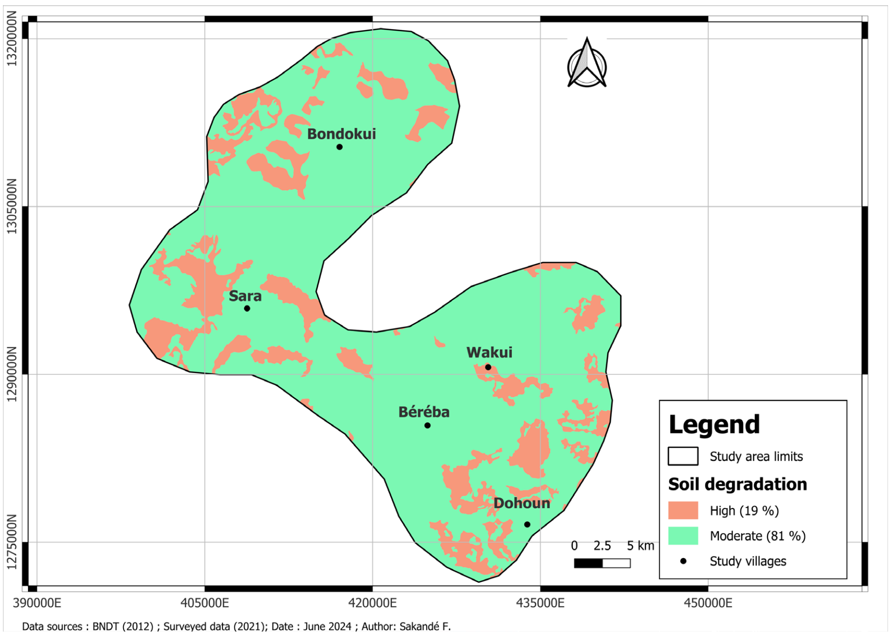

Figure 8. State of degradation of soils in the study area in western Burkina Faso. The map categorizes soil degradation into two levels: high degradation (19% of the area, shown in brown) and moderate degradation (81% of the area, shown in green).

3.3. Influence of Land Use Patterns on Soil Degradation

The Soil Degradation Index (SDI) reveals that the land use patterns have impacted all studied soil physico-chemical parameters (Figure 9). SDI values indicate a reduction of more than 20% in OM, CEC, N, K, and clay contents in crop lands compared to their respective levels in protected forests (Figure 9). Silt content and soil current acidity also decreased (by less than 20%), but to a lesser extent than other soil parameters. In contrast, P and sand contents increased by 26.9% and 19.6%, respectively (Figure 9).

In pasturelands, OM, N, K contents, CEC, and soil clay content were similarly the most negatively affected (Figure 9). However, P and sand contents increased by 0.8% and 22.1% respectively, although these increases were smaller than those observed in crop lands (Figure 9).

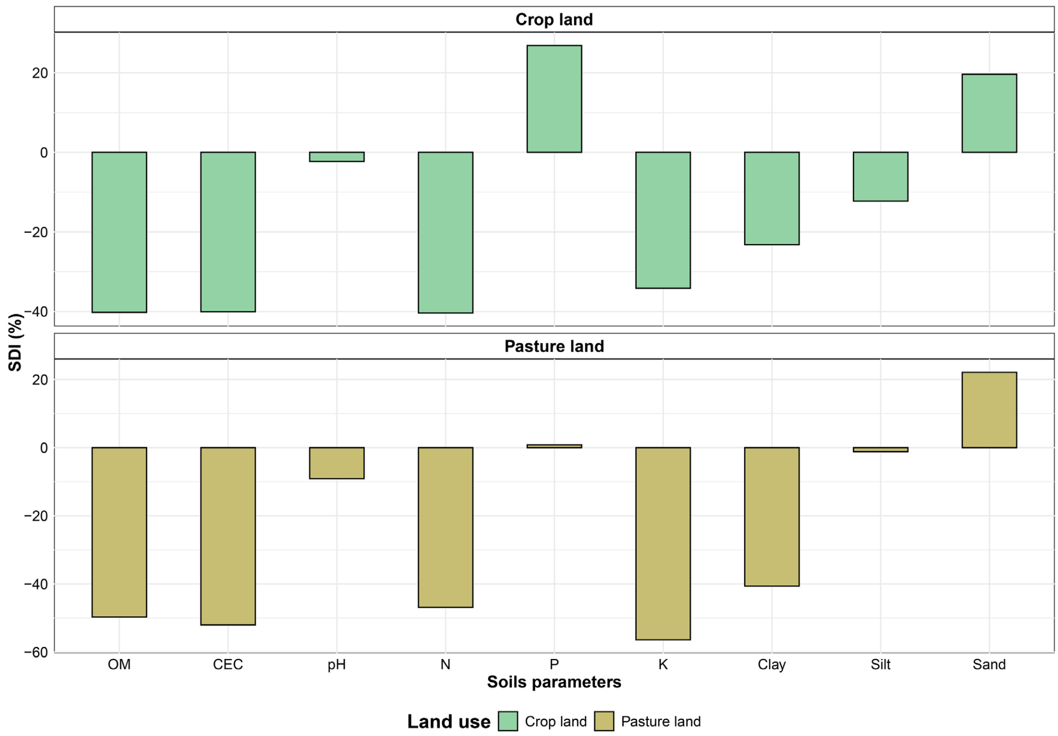

Figure 9. Soil Degradation Index (SDI) as affected by land use pattern (cropland and pastureland). The SDI values, expressed as percentages, illustrate the relative degradation levels of Organic Matter (OM), Cation Exchange Capacity (CEC), pH (H_2O), nitrogen (N), phosphorus (P), potassium (K), clay (%), silt (%), and sand (%). Green bars represent cropland, while yellow bars represent pasturelands. Negative values indicate a decrease in soil quality relative to the baseline, *i.e.* the protected forest.

4. Discussion

The results of this study reveal an alarming state of soil degradation in the western cotton-growing region of Burkina Faso. The spatial distribution of soil physico-chemical parameters highlights the region's vulnerability to degradation, with widespread deficiencies in essential nutrients, high acidity, and pronounced erosion influenced by topography.

Over 95% of soils in the study area exhibit OM levels below 2%, underscoring their intrinsic fragility, as OM is crucial for soil structure, moisture retention, nutrient cycling [30]. This low OM content can be partially attributed to the intensive use of land for cotton production, a longstanding practice in this area. Marginal lands, typically located on upper slopes, and serving as buffer zones to regulate runoff and reduce erosion, have been increasingly cultivated, exacerbating the effects of water erosion. Additionally, rising land pressure greatly reduced fallowing, a traditional soil fertility management practice, further contributing to OM decline [11] [31]. However, the causes of soil degradation mentioned above would likely not lead to such a drastic drop in soil carbon content if adequate soil fertility management methods were adopted on the agricultural plots and pasturelands. Current farming practices, which include reduced organic inputs due to crops residues exportation and intensive ploughing, not only limit OM recycling but also accelerate the mineralization of the few crop residues left on the fields.

The soil acidity (pH (H_2O) < 6.5 for more than 90% of soils in the investigation area) is also a limiting factor for sustainable crops production in the area. This acidification may be linked to the local fertilization practices which primarily rely on mineral fertilizers, specifically NPK + S + B (14-18-18 + 6S + B) and urea (46% of N), as noted in our investigation, as well as Koulibaly *et al.* [13]. The acidification process occurs through the release of hydrogen ions (H+) during the nitrification of ammonium-based fertilizers, where $NH4^+$ is oxidized to $NO3^-$, generating H^+ ions that lower soil pH. Additionally, the low contribution of organic amendments through the recycling of crop residues and cattle manure, as already mentioned above, could also explain the acidification of farmlands. Low CEC levels (very low in 54% of the area and low in another 44%) along with widespread nitrogen and phosphorus deficiencies over 75% of soils fall within the low nitrogen class and assimilable phosphorus values range from 0.7 to 13.4 mg kg−1, confirm severe nutrients depletion. This depletion likely results from unsustainable soil fertility management practices and other farming operations. Research in the region has shown that farmers apply less fertilizer than recommended, resulting in soil nutrient deficits [11] [32]. Soil acidity likely exacerbates nutrient loss; as observed by Zingore *et al.* [4] soil acidification is a recurring issue in intensive cropping systems across sub-Saharan Africa.

The Soil Degradation Index (SDI) showed that land use patterns strongly affect soil physico-chemical properties, indicating a substantial reduction in OM, CEC, N, K and clay contents in cultivated fields compared to forest areas, with croplands experiencing more intensive degradation than pasture lands. Similar findings were reported by Ouattara *et al.* [33] and Koulibaly *et al.* [34]. Several authors also observed this trend of OM decline in relation to land use patterns, attributing it to agricultural intensification and the reduction of fallow periods [35] [36].

Topography significantly influenced the soil particle size distribution, with a significant accumulation of clay on lower slopes and sand more concentrated on upper slopes. This distribution suggests a differentiated erosion process, exacerbated by the conversion of marginal lands to farms. As mentioned above, shallow soils on upper slopes, historically buffer zones uncultivated for grazing or forest products harvesting, now experience intensified erosion due to increased cultivation and low vegetation cover. The resulting increased runoff speed likely resulted in greater leaching of clay particles from the upper to the lower slopes. Similar cases of soil erosion have been reported by Okou *et al.* [37] and Atchada *et al.* [38]. This erosion reduced nutrient retention due to the dominant sandy texture of the soil. Consequently, continues leaching leads to soil degradation in the western cotton-farming zone of Burkina Faso. Ouattara *et al.* [33] and Koulibaly *et al.* [39] established a link between soil structure degradation, decreased CEC, and nutrient deficiencies in cotton-based farming systems in Burkina Faso.

Considering the overall state of soil degradation, the results report "moderate" to "high" degradation levels over the entire study area with variations across physiographic units. This trend aligns with findings obtained by Sawadogo [40] in Burkina Faso and reflects the broader trend of land degradation in West Africa [41] [42]. The more pronounced degradation observed on ferruginous soils at the top of slopes highlights the role of topography in degradation processes and reflects the increased fragility of tropical ferruginous soils, particularly susceptible to erosion and degradation [43] [44].

The findings of our investigation emphasize the urgent need for sustainable land management practices to restore and maintain soil fertility in the western cotton zone of Burkina Faso. Integrated approaches to soil fertility management, combining OM application, mineral fertilizers and soil conservation techniques, should be considered to reverse the trend of degradation [41] [45]. Specific policy interventions should include targeted subsidies for compost application and cover cropping to address the critical lack of organic matter, as well as incentives for reduced tillage practices. Furthermore, the establishment of integrated agro-sylvo-pastoral systems could also promote better synergy among different land uses, supporting more sustainable soil resources management [46] [47].

This study provides a snapshot of soil conditions in a specific region and timeframe. However, seasonal variations and sample limitations could influence the generalizability of these findings. While the 32 samples collected in this study provide a critical baseline for understanding soil degradation patterns in the region, future research using a higher sampling density would improve the resolution and accuracy of the spatial interpolation maps. Moreover, future research should focus on long-term monitoring of sustainable conservation practices across diverse physiographic units and investigate seasonal fluctuations in soil health indicators to deepen the understanding of soil degradation dynamics. Additionally, studies on the socioeconomic impact of soil degradation on local communities would clarify how soil health affects agricultural productivity, food security, and livelihoods. Research in this direction could help inform policies that promote sustainable land management and address the socioeconomic needs of the region's population.

5. Conclusions

This study highlights severe soil resource degradation in the western cotton-growing region of Burkina Faso, characterized by a significant spatial heterogeneity in soil physico-chemical parameters. The findings indicate a predominance of soils low in OM, acidic, and deficient in essential macro-nutrients for agricultural productivity. Topography plays a critical role in the distribution of physical soil parameters, emphasizing the impact of erosion on soil degradation dynamics. Degradation levels vary from "moderate" to "strong" across physiographic units, with ferruginous soils on upper slopes facing particularly severe conditions. This variability highlighting the need for context-specific soil fertility management approaches.

The analysis of the impact of land use patterns shows more pronounced degradation in croplands than in pasture lands, compared to non-cultivated protected forest areas, underscoring the urgency of adopting sustainable land management practices in this important agricultural region. Integrated approaches that combining the judicious use of OM, mineral fertilizers and soil conservation techniques are essential to restore and maintain soil fertility.

Finally, this study suggests that future research should focus on evaluating the long-term efficacy of soil management practices across different physiographic units to further inform policies that promote sustainable land management in the region.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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