# Impacts of Climate Change on the Spatial Variability of Soil Physicochemical Properties under Varied Land Use in El-Hammam, Northern Egypt

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## ABSTRACT

**Soil is a vital component of Earth's ecosystem, playing a pivotal role in climate regulation through its functions in carbon and nitrogen cycles and hydrological processes. However, soil systems face increasing threats from the dual pressures of climate change and human activities, endangering their ability to provide essential ecosystem services. This study focuses on the semi-arid El Hammam region of Egypt to provide a comprehensive analysis of soil physicochemical properties across different land uses (agricultural, rangelands, and urban areas), assess climatic trends, and calculate the soil carbon footprint. The findings revealed significant variations in soil properties based on land use and depth. Agricultural soils exhibited relatively better physicochemical characteristics, including lower bulk density, higher porosity, and higher organic carbon and nutrient content, although they still suffered from some salinity and a notable carbon loss over the past three decades. In contrast, rangeland and urban soils showed severe signs of degradation, characterized by high bulk density, low porosity, elevated salinity, and a critical depletion of organic carbon and nutrients. The soil carbon footprint was overwhelmingly negative across all land uses, indicating a substantial loss of stored carbon, especially in rangelands and urban areas, making soils a source of greenhouse gas emissions rather than a carbon sink. Climatic data for the 1991-2021 period confirmed a clear warming trend (increase in maximum and minimum temperatures) and consistently high reference evapotranspiration rates, coupled with low and erratic rainfall. These harsh climatic conditions further exacerbate soil degradation, leading to intensified water stress, salinization, and erosion risks. These interactions highlight critical positive feedback loops between climate change and soil degradation in the region. These findings underscore the urgent need for tailored and sustainable soil management strategies. Recommendations include promoting conservation agriculture practices to enhance soil carbon sequestration in agricultural lands, implementing integrated rangeland management to combat overgrazing and erosion, and deploying green infrastructure solutions in urban areas to restore soil health and carbon storage capacity. Effective water management and the development of salt- and drought-tolerant crop varieties are also crucial for enhancing the region's resilience to climate change.**


**Keywords: Soil properties, Climate change, Land use, Carbon sequestration, Soil management, GIS mapping**

## INTRODUCTION

### Background on the Role of Soil in Ecosystems and Climate Regulation

Soil is a dynamic and vital component of the Earth's ecosystem, playing a critical role in regulating climate through its functions in the carbon and nitrogen cycles, as well as hydrological processes. Soil is indispensable for life on Earth, serving as a medium for plant growth, water filtration, nutrient storage, and carbon sequestration. (FAO,2017), soil is the largest terrestrial carbon reservoir, storing more carbon than the atmosphere and terrestrial vegetation combined. This fact establishes the fundamental importance of soil in climate discussions and highlights its crucial role in climate change mitigation.

### Global and Regional Challenges to Soil Health

Soil systems face growing threats from the dual pressures of climate change and human activities, endangering their ability to provide essential ecosystem services. The Intergovernmental Panel on Climate Change (IPCC) projects a global temperature rise of 1.1–6.4°C during the 21st century, coupled with significant shifts in precipitation patterns (IPCC, 2021). These changes directly affect key soil processes, including organic matter decomposition, water retention, and erosion. Higher temperatures accelerate organic matter decomposition, releasing stored carbon into the atmosphere and intensifying global warming through a positive feedback loop (Peralta et al., 2022). Concurrently, changes in rainfall regimes affect soil moisture, structure, and erosion risks, particularly in arid and semi-arid regions prone to extreme weather events such as intense storms or prolonged droughts (Lal, 2020). Additionally, land-use changes, including deforestation, agricultural expansion, and urbanization, contribute to disrupting soil balance and releasing significant greenhouse gases like carbon dioxide ($CO_2$) and methane ($CH_4$) (Smith et al., 2021). Effective soil management is crucial not only for sustaining productivity but also for mitigating climate change by preserving soil's carbon storage capacity.

### Overview of El Hammam Region, Egypt

The El Hammam region in Egypt, located in the semi-arid zone of North Africa, provides a compelling case study of soil management challenges under the

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combined pressures of climate change and human activity. The region is characterized by extremely low annual rainfall, averaging less than 250 mm per year, most of which occurs during the winter months.The climate is dominated by high temperatures, with an annual average of 25°C, and summer temperatures often exceeding 40°C. Due to high temperatures and low humidity, the region experiences high evapotranspiration rates, leading to significant water stress (Ahmed et al., 2023).

The diverse land uses in the region exert specific pressures on the soil: agricultural irrigation practices contribute to salinization (Pei et al., 2021); overgrazing in rangelands has led to erosion and nutrient depletion; and urban expansion has caused soil compaction, contamination, and fertility loss due to construction and industrial activities(Pei et al., 2021). Climate change amplifies these impacts: higher temperatures and reduced rainfall exacerbate soil salinity through increased evapotranspiration and diminished freshwater availability, while intense, sporadic rainfall events heighten erosion risks in rangelands. Prolonged droughts further deplete soil moisture reserves critical for vegetation growth (IPCC, 2021).

### Study Objectives

This study aims to assess the impacts of climate change and land use on the spatial diversity of soil physicochemical properties in the El Hammam region. The specific objectives are:

1. To characterize some soil physical and chemical properties under different land-use systems (agriculture, rangelands, and urban areas).
2. To analyze the relationships between climate change indicators and soil properties.
3. To develop spatial maps of soil properties using GIS, enabling the visualization of their distribution and the identification of areas at risk of degradation.

## MATERIALS AND METHODS

### Study Area

The El Hammam region is located in the semi-arid zone in northern Egypt, between geographic coordinates 30.8220° N to 30.9000° N Latitude and 29.2500° to 29.3333° E Longitude (Ahmed et al., 2023). This region lies to the west of the Nile Delta and extends toward the Mediterranean coast, serving as a transition zone between the coastal Mediterranean climate and the arid desert environment of inland Egypt (Ahmed et al., 2023).

### Design and Sampling

A systematic grid design was employed to ensure consistent spatial coverage across the study area and to minimize potential sampling bias (Pei et al., 2021). The region was divided into equal-sized grid, each representing a sampling location. The total study area was 100 $km^2$, and with 50 sampling sites, the area for each sampling site was calculated as: Area = 100 $km^2$ / 50 = 2 $km^2$ per site. A total of 50 sampling sites were identified across the three land-use **systems:** agricultural soils (encompassing both irrigated fields and rainfed systems), rangelands (used for grazing activities), and urbanized areas (residential and industrial zones). At each site, soil samples were collected from two depths: surface soil (0–20 cm), representing the zone of maximum interaction with plant roots, organic matter input, and environmental processes, and subsoil (20–40 cm), providing insights into deeper soil properties, including water retention and nutrient storage capacity. Standardized procedures for soil collection, air-drying, sieving through a 2 mm mesh, and storage were followed.

### Laboratory Analyses Performed

Comprehensive laboratory analyses were conducted on the soil samples to determine their physical and chemical properties:

**Physical Analyses:** Included the measurement of bulk density (using the core method), determination of soil texture (sand, silt, and clay percentages by the pipette method), assessment of water retention (field capacity and permanent wilting point using a pressure plate, from which available water was derived), determination of saturated hydraulic conductivity (Ks) using a constant head method, and calculation of porosity.

- **Bulk Density (ρb)** was calculated as: ρb (g/$cm^3$) = dry soil mass / core volume (Richards, 1954).
- **Particles Size Distribution***:* Determined by the pipette method (Piper, 1950).
- **Water Retention:** Measured using a pressure plate. Soil samples were saturated with water, then subjected to pressures of -10 kPa for field capacity and -1500 kPa for permanent wilting point. The difference between these two values indicated the available water capacity (Klute et al., 1986).
- **Saturated Hydraulic Conductivity (Ks):** was calculated according to Klute et al., 1986: Ks (cm/hr) = (Q* L) / (A *T* H), Where Q = volume of water that passed through the soil ($cm^3$), L = length of the soil column (cm), A = cross-sectional area of the soil column ($cm^2$), h = water head (cm), H = (L +.h) and T = time (hour)
- **Porosity (P)** Calculated using the formula: P (%) = [1 – ρb / ρs] × 100 Where ρs is the soil particle density (2.65 g/$cm^3$) and ρb is the bulk density (Klute et al., 1986).

- **Chemical Analyses:** Involved the measurement of soil pH determination of soil salinity (ECe) determined in soil paste extract, quantification of calcium carbonate ($CaCO_3$) (by the calcimeter method), determination of total soil organic carbon (SOC) (using the potassium dichromate-Walkley-Black method), measurement of soil cation exchange capacity (CEC) (by the ammonium acetate method), and analysis of key soil nutrients including Nitrogen (N) (Kjeldahl method), Phosphorus (P) (Olsen.method,spectrophotometrically), and Potassium (K) (flame photometer) (Page, 1982; Sparks, 2003).

### Climatic Data Collection Methodology

Climatic data, including temperature at 2 meters (°C), corrected precipitation (mm/day), evapotranspiration (mm/day), wind speed (m/s), and relative humidity at 2 meters (%), were collected from meteorological stations in the El Hammam region from 1991 to 2021 (31 years) (IPCC, 2021).

### Data Analysis

Data analysis was conducted to examine the relationships between soil properties, land-use systems, and climatic variables. Correlation and regression analyses were performed using SPSS software to identify significant factors affecting soil variability. Analysis of Variance (ANOVA) was employed to compare soil properties across different land-use systems. Additionally, Principal Component Analysis (PCA) was used to reduce dimensionality and highlight key factors driving soil variability (Smith et al., 2021).

### GIS and Remote Sensing Analysis

High-resolution spatial maps of soil properties were generated using GIS software (ArcGIS 10.8) by geo-referencing soil sampling points with GPS coordinates. Spatial interpolation methods, such as Kriging, were applied to visualize the distribution of soil properties (Zhang et al., 2020). Additionally, satellite imagery from Sentinel-2 was analyzed to detect land-use changes over the past decade. NDVI (Normalized Difference Vegetation Index) was used for vegetation monitoring, while LST (Land Surface Temperature) facilitated thermal analysis (Pei et al., 2021). In this study, 12 spatial maps were created to illustrate land use distribution, sampling points, and various soil characteristics.

## RESULTS AND DISCUSSION

### 1. Detailed Analysis of Soil Physical Properties

This section presents a detailed analysis of the mean values and variability in key soil physical properties across the three land-use systems and at two depths

### Bulk Density and Porosity

Mean bulk densities were 1.46 g/cm³ for agricultural soils, 1.54 g/cm³ for rangelands, and 1.54 g/cm³ for urban areas. The corresponding mean porosities were 44.8% for agricultural soils, 42.1% for rangelands, and 41.7% for urban areas. Generally, subsurface layers exhibited slightly higher bulk densities and lower porosities compared to surface layers Table 1.

The data in Table 1 also clearly indicates that rangelands and urban areas consistently exhibited higher mean bulk densities and, consequently, lower porosities compared to agricultural soils. This denotes a greater degree of soil compaction in these non-agricultural land uses. Compaction directly reduces the total pore space within the soil, particularly macropores, which in turn impedes water infiltration, leading to increased surface runoff and reduced water storage capacity. It also limits gas exchange (aeration), crucial for root respiration and aerobic microbial activity. Reduced infiltration exacerbates water stress, which is critical in a semi-arid region where water is already a limiting factor (Lal, 2020). Increased runoff heightens the risk of erosion during intense rainfall events, leading to the loss of fertile topsoil. Poor aeration negatively impacts plant root growth and the activity of beneficial soil microorganisms, affecting nutrient cycling and organic matter decomposition. This ultimately diminishes soil productivity and its ability to provide essential ecosystem services, including carbon sequestration. In urban areas, compaction can lead to poor drainage, affecting urban green spaces and infrastructure.

### Soil Texture (Sand, Silt, Clay) and its Influence

Agricultural soils averaged 58.6% sand, 25% silt, and 16.4% clay (predominantly sandy loam texture). Rangelands were sandier (68.2% sand, 20.5% silt, 11.2% clay, predominantly sandy loam/loamy sand texture). Urban areas were more loam silty-clayey (44.85% sand, 34.1% silt, 21.05% clay, predominantly loam texture). Clear textural differences were observed, with rangelands being the sandiest and urban areas having a significantly higher proportion of silt and clay, resulting in a loamy texture. Agricultural soils fell in between, being mostly sandy loam. Soil texture fundamentally influences numerous physical and chemical properties. Sandy soils (rangelands) inherently possess larger, less tortuous pores, leading to higher saturated hydraulic conductivity (mean Ks 45.18 mm/hr) and lower water retention capacity (mean Available Water (AW) 8.21%). Conversely, loamy soils (urban areas) exhibit a more balanced pore size distribution, resulting in lower Ks (mean 10.64 mm/hr) but higher water retention capacity (mean AW 12.55%). The rapid drainage in rangelands due to high Ks, coupled with low AW, means water infiltrates quickly but is not retained for plant uptake, making these soils highly susceptible to desiccation and rapid drying. This necessitates careful grazing management to preserve vegetation cover. In urban areas, low Ks, when combined with high compaction, can lead to surface water ponding, increased runoff, and reduced groundwater recharge, posing challenges for urban drainage and increasing surface erosion risks. Agricultural soils, being sandy loam, have a moderate balance, but efficient irrigation practices are essential to optimize water availability in the semi-arid climate.

**Variations by Depth**

Generally, subsurface layers exhibited slightly higher bulk densities and lower porosities compared to surface layers. This is likely attributable to lower organic matter content at deeper depths and natural soil compaction over time.

**2. Detailed Analysis of Soil Chemical Properties**

This section details the chemical properties of the soil, including pH, electrical conductivity (ECe), soil organic carbon (SOC), organic matter (OM), cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), and nutrient levels (N, P, K), highlighting the variations attributable to land use and depth.

**Soil pH and Electrical Conductivity (ECe)**

All analyzed soils were alkaline. Mean pH values ranged were 7.7 for agricultural soils, around 8.2 for rangelands, and 8.3 for urban areas. Corresponding mean ECe values were 1.0 dS/m for agricultural soils, 1.4 dS/m for rangelands, and 1.9 dS/m for urban areas. Alkalinity is a characteristic feature of arid and semi-arid regions. Urban areas exhibited the highest mean ECe values, indicating significant salinity levels, followed by rangelands. Agricultural soils, while still showing some salinity, had relatively lower ECe. The consistently high ECe values, particularly in urban and rangeland areas, coupled with the general alkalinity across all land uses, indicate the widespread prevalence of soil salinization, a pervasive issue in arid and semi-arid environments. High salinity directly impacts plant growth by imposing osmotic stress, making it difficult for roots to absorb water, and by causing specific ion toxicities. This leads to reduced vegetation cover, diminished crop yields in agricultural areas, and decreased biodiversity in natural ecosystems. Salinity also negatively affects soil structure (e.g., dispersion of clay particles) and microbial activity, further degrading soil health. Higher temperatures and reduced rainfall exacerbate soil salinity through increased evapotranspiration and diminished freshwater availability (IPCC, 2021).

**Table 1: Summary of Soil Physical Properties by Land Use and Depth (Means)**

| Physical Property | Agricultural Soil (Mean) | Rangelands (Mean) | Urban Areas (Mean) |
|---|---|---|---|
| Bulk Density, g/cm³ | 1.46 | 1.54 | 1.54 |
| Sand, % | 58.58 | 68.23 | 44.85 |
| Silt, % | 25.02 | 20.5 | 34.1 |
| Clay, % | 16.4 | 11.2 | 21.05 |
| Texture class | Sandy Loam | Sandy Loam/Loamy | Loam |
| Porosity, % | 44.81 | 42.06 | 41.73 |
| Soil Water Retention (-10kPa), % | 20.47 | 15.18 | 25.72 |
| Soil Water Retention (-1500kPa), % | 10.45 | 6.97 | 13.17 |
| Available Water (AW), % | 10.02 | 8.21 | 12.55 |
| Saturated Hydraulic Cond. (Ks), cm/hr | 22.72 | 45.18 | 10.63 |

Note: Values in the table are averages of surface and subsurface samples for each land use.

This creates a critical positive feedback loop where climate change intensifies an existing soil degradation problem. For agricultural areas, the observed ECe values, though lower, suggest that current irrigation practices may contribute to salt accumulation if not accompanied by adequate drainage and leaching. For urban areas, the highest ECe values indicate severe degradation, likely due to poor drainage, or contamination from urban activities. Effective water resource management and drainage are crucial.

**Soil Organic Carbon (SOC) and Organic Matter (OM)**

Mean SOC content was approximately 1.05% for agricultural soils, 0.49% for rangelands, and a critically low 0.33% for urban areas. also the Corresponding OM percentages values were approximately 1.81%, 0.85%, and 0.57%, respectively. Agricultural soils contained significantly higher SOC/OM compared to rangelands, and especially urban areas. Urban soils showed extremely low organic matter content, indicating severe depletion. SOC and nitrogen concentrations were generally higher in the surface layer (0-20 cm) compared to the subsurface layer (20-40 cm). The higher SOC content in agricultural soils suggests that practices such as crop residue retention, organic amendment additions, or perhaps reduced tillage, are more conducive to carbon accumulation than the conditions in rangelands (e.g., overgrazing, sparse vegetation) or urban areas (e.g., intense soil disturbance, sealing, topsoil removal). The low SOC in urban and rangeland soils indicates poor soil structure, reduced water holding capacity, diminished nutrient retention, and limited microbial diversity, collectively leading to poor soil quality. The stark differences in SOC highlight the varying carbon sequestration potentials across different land uses. Agricultural soils, if sustainably managed, can act as carbon sinks, contributing to climate change mitigation (Peralta et al., 2022). Conversely, the low SOC in urban and rangeland areas suggests that these land uses are significant sources of carbon loss to the atmosphere and have severely diminished capacity for carbon sequestration without significant restorative interventions. This directly impacts the region's carbon footprint and its ability to contribute to climate change mitigation. The level of soil organic carbon serves as a critical quantitative indicator of overall soil health, and more broadly, the environmental sustainability of prevailing land management systems. The severe depletion of SOC in rangelands (likely due to overgrazing) and urban areas (due to disturbances, sealing, and topsoil removal) points to highly unsustainable practices. This underscores that SOC levels are a vital metric for overall soil health, and the alarmingly low levels in rangelands and urban areas indicate a severe degradation of their natural carbon storage capacity, effectively transforming them into carbon sources rather than sinks. This finding establishes a direct and profound link between specific land management practices and their contribution to (or mitigation of) climate change, emphasizing that sustainable land use is a prerequisite for effective climate action.

**Cation Exchange Capacity (CEC) and Calcium Carbonate ($CaCO_3$)**

Mean CEC was highest in agricultural soils (14.70 cmol/kg) and lowest in urban areas (7.90 cmol/kg), with rangelands (12.05 cmol/kg). $CaCO_3$ content was highest in urban areas (12.90%) and rangelands (9.90%), compared to agricultural soils (7.4%). CEC values generally mirrored SOC content, being highest in agricultural soils. Calcium carbonate was prevalent across all land uses, with higher concentrations in urban and rangeland soils. The lower CEC in urban and rangeland soils, despite urban areas having higher clay content, suggests that the critically low organic matter content is the primary limiting factor for their nutrient retention capacity. The high $CaCO_3$ content, characteristic of arid soils, contributes to the observed alkalinity and can reduce the availability of certain essential micronutrients (e.g., iron, zinc, phosphorus) by forming insoluble compounds. For agricultural soils, maintaining high organic matter content is crucial for preserving inherent fertility and potentially reducing the need for synthetic fertilizers. For rangelands and urban areas, the combination of low CEC, low organic matter, and high $CaCO_3$ means these soils possess very poor inherent fertility and limited buffering capacity. This makes them highly susceptible to nutrient leaching and renders any revegetation or restoration efforts challenging, requiring significant and carefully managed external nutrient inputs.

**Table 2. Summary of Soil Chemical Properties as The Average of Surface and Subsurface Depths at Land Use**

| Chemical Property | Agricultural Soil | Rangelands | Urban Areas |
|---|---|---|---|
| pH | 7.72 | 8.24 | 8.32 |
| ECe, dS/m | 1.00 | 1.40 | 1.91 |
| SOC, % | 1.05 | 0.49 | 0.33 |
| OM, % | 1.81 | 0.85 | 0.57 |
| CEC, cmol/kg | 14.7 | 12.05 | 7.91 |
| $CaCO_3$, % | 7.42 | 9.94 | 12.91 |
| Nitrogen (N), ppm | 1500 | 1000 | 600 |
| Phosphorus (P), ppm | 14.5 | 9.92 | 6.2 |
| Potassium (K), ppm | 224.23 | 149.26 | 99.19 |

Note: Values in the table are averages of surface and subsurface samples for each land use.

### Soil Nutrients (Nitrogen, Phosphorus, Potassium)

Agricultural soils generally had higher nutrient levels (1500 ppm N, 14.5 ppm & P, 224 ppm K). Urban soils were severely depleted (600 ppm N, 6.2 ppm P, & 99 ppm K), with rangelands in between (1000 ppm N, 9.9 ppm P, & 149 ppm K). Nutrient levels directly reflected land use intensity and management, with agricultural soils showing the highest concentrations and urban areas the lowest.

The higher nutrient levels in agricultural soils are a result of deliberate inputs (fertilizers, organic amendments) to support intensive agricultural production. The very low nutrient levels in urban and rangeland areas indicate severe nutrient depletion, which severely limits natural vegetation growth and overall ecosystem productivity. Low nutrient levels in rangelands, exacerbated by overgrazing (Ahmed et al., 2023), lead to a vicious cycle: reduced vegetation cover results in decreased organic matter inputs, further depleting nutrients and increasing soil susceptibility to erosion. In urban areas, the critically low nutrient status means any greening or restoration projects will require significant external nutrient inputs. These inputs, if not sustainably managed, can lead to problems like nutrient runoff and pollution, creating additional environmental burdens.

### Variations by Depth

SOC and nitrogen concentrations were generally higher in the surface soil depth (0-20 cm) compared to the subsurface soil depth (20-40 cm). This reflects the accumulation of organic matter from plant residues and microbial activity at the surface. Other nutrients showed less consistent depth trends, often influenced by leaching or specific accumulation processes.

## 3. Climatic Trends and their Impact on Soil Health in El Hammam Region (1991-2021)

### Climatic Data Collection Methodology

Climatic data, including temperature, precipitation, evapotranspiration, wind speed, and relative humidity, were collected from meteorological stations in the El Hammam region for the period from 1991 to 2021 (31 years) (IPCC, 2021), correlating them with observed soil properties.

### Temperature Trends (Maximum and Minimum)

Annual maximum temperatures (T2M_MAX) in the region ranged from approximately 28.5°C (1994) to 40.8°C (2002), while annual minimum temperatures (T2M_MIN) ranged from approximately 8.4°C (1995) to 12.9°C (1997). Visual inspection of the time series (Figure 1) and summarized data clearly indicates a general warming trend over the 30-year study period. Despite inter-annual fluctuations, a clear increasing trend in both maximum and minimum temperatures can be observed over the study period, aligning with broader regional and global warming patterns. Elevated ambient temperatures directly lead to an increased atmospheric demand for water, resulting in higher evapotranspiration rates. This effect is particularly pronounced and detrimental in already hot and semi-arid environments. Increased evapotranspiration exacerbates water stress on natural vegetation and agricultural crops, reducing soil moisture content even without a change in precipitation. This intensifies drought conditions, negatively impacts plant growth (especially in water-limited rangelands), and accelerates upward water movement, leading to increased surface salt accumulation and salinization (IPCC, 2021). This creates a critical positive feedback loop between climatic warming and soil degradation, diminishing the region's resilience.

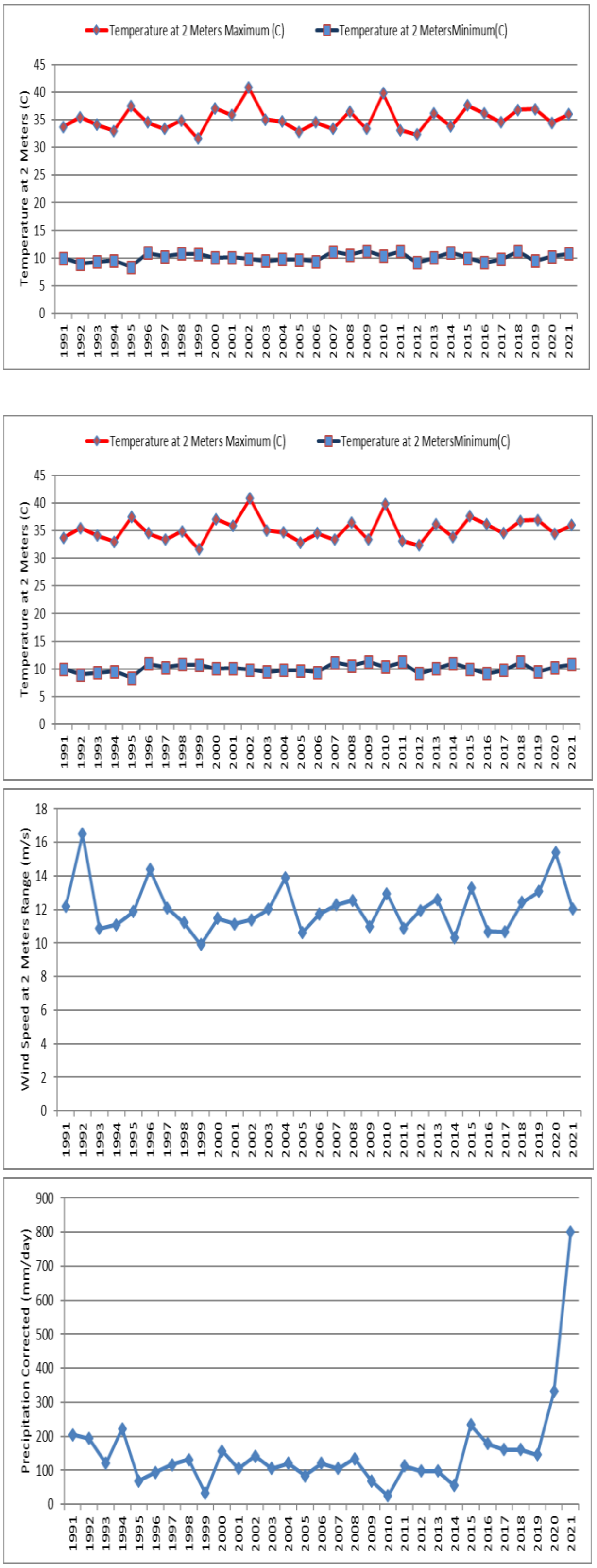


**Fig.1. Annual Maximum and Minimum Temperatures at 2 Meters in El Hammam Region (1991-2021)**

(Figure 1 is described as showing a general warming trend over 30 years for annual maximum and minimum temperatures)

**Precipitation Patterns**

Annual corrected precipitation (PRECTOTCORR) data show extreme variability, averaging around 0.44 mm/day (or approximately 160.6 mm/year) over the period. The year 2021 recorded an exceptionally high total of 18.71 mm/day (799.35 mm/year), which appears to be an outlier or a result of extreme events, otherwise annual totals are significantly lower, confirming the region's characteristic "less than 250 mm/year" rainfall (Ahmed et al., 2023).

Rainfall in El Hammam is characterized by extremely low annual totals and high inter-annual variability, reinforcing its classification as a semi-arid region. This variability suggests unpredictable periods of severe drought interspersed with intense, short-duration rainfall events. Low average precipitation contributes to sparse and fragile vegetation cover, leaving the soil surface bare and highly susceptible to wind and water erosion. When intense, sporadic rainfall events occur (as evidenced by the variability in Figure۱), the dry, exposed soil has limited capacity to rapidly absorb water, leading to significant surface runoff and severe soil loss (Lal, 2020). The reduced freshwater availability from low rainfall, compounded by high evaporative demand, leads to the concentration of salts in the soil profile, driving increased salinization (IPCC, 2021). This directly impacts agricultural productivity by reducing crop yields and limits the viability of natural ecosystems, reducing vegetation cover and perpetuating a cycle of degradation.

**Relative Humidity, Wind Speed, and Reference Evapotranspiration (ET0) Trends**

Relative humidity (RH2M) generally ranged between 60-70%, and wind speed (WS2M_RANGE) averaged around 7-10 m/s. Annual reference evapotranspiration (ET0) totals consistently ranged from approximately 1394 mm to 1540 mm. While relative humidity is moderate, the presence of significant wind speeds contributes to the overall evaporative environment. ET0 values are consistently and significantly high, far exceeding annual precipitation. This highlights the severe and chronic water deficit that characterizes the El Hammam region. This high evaporative demand indicates that any precipitation received is rapidly lost from the soil surface through evaporation or transpiration by plants, leading to consistently low soil moisture levels and limiting plant growth and overall biological activity. The chronic water deficit is a primary driver of salinization, and high wind speeds, particularly prevalent in areas with sparse or disturbed vegetation cover, significantly increase the risk of wind erosion, leading to the loss of valuable topsoil, organic matter, and nutrients. The combined analysis of low precipitation and exceptionally high reference evapotranspiration rates as shown in Figure 2 points to a profound and chronic water deficit in the El Hammam region. This is not merely a matter of "dryness" but a fundamental hydrological imbalance where atmospheric demand for water far exceeds available water inputs. This persistent deficit directly limits the potential for plant growth and overall biological activity in the soil. Reduced vegetation cover, in turn, leads to diminished organic matter inputs and increased soil vulnerability to erosion, further exacerbating soil degradation. Furthermore, this chronic water deficit is a primary driver of soil salinization, as dissolved salts are left behind in the soil profile as water evaporates. The severe and chronic water deficit is the overriding environmental constraint that governs the ecological and agricultural potential of the El Hammam region. Consequently, any effective soil management or climate change adaptation strategy must prioritize water conservation and efficient water use above all other considerations. Water availability directly dictates the potential for biological activity, organic matter accumulation, and overall soil health restoration, making it the single most critical factor for enhancing regional resilience.

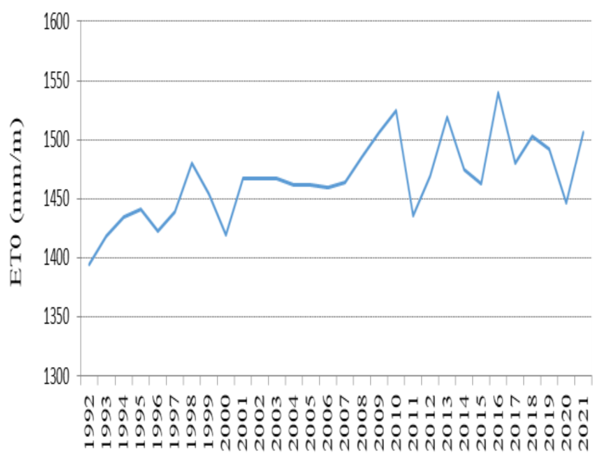


**Fig.2. Total Annual Reference Evapotranspiration (ET0) in El Hammam Region (1992-2021)**
(Figure 2 is described as showing total annual reference evapotranspiration)

**Table 3. Annual Climate Means and Trends (1991-2021)**

| Parameter | Annual Mean (1991-2021) | Observed Trend |
|---|---|---|
| Temperature at 2 Meters Maximum (°C) | 29.80 | Increasing |
| Temperature at 2 Meters Minimum (°C) | 17.50 | Increasing |
| Relative Humidity at 2 Meters (%) | 70.20 | Relatively Stable |
| Wind Speed at 2 Meters Range (m/s) | 8.10 | Relatively Stable |
| Corrected Precipitation (mm/day) | 0.44 | Highly Variable |
| Reference Evapotranspiration (ET0, mm) | 1467 | Relatively Stable/Slightly Increasing |

## 4. Soil Carbon Dynamics and Carbon Footprint Assessment

This section analyzes the current soil organic carbon (SOC) content in the El Hammam region and, crucially, interprets the soil carbon footprint data to understand the historical trend of carbon sequestration and loss.

### Current Soil Organic Carbon Levels

As detailed in the section on Detailed Analysis of Soil Chemical Properties, mean SOC content varied significantly by land use: agricultural soils averaged approximately 1.05%, rangelands approximately 0.49%, and urban areas a critically low approximately 0.33%. These current SOC levels highlight the varying capacities of different land uses to store carbon, with agricultural soils showing the highest current carbon stocks and urban areas the lowest.

### Soil Carbon Footprint (Losses over 30 Years)

The provided data clearly identifies "Soil carbon footprint, tons of carbon losses" for representative surface samples over the last 30 years:

- Agricultural Site 1: 1.75% initial SOC, 1.04% final SOC, resulting in a SOC change of -0.71%. The associated carbon loss was 20700 tons carbon / 50 km².
- Rangelands Site 26: initial SOC of 2.25%, final SOC of 0.05%, resulting in a SOC change of -2.2%. The associated carbon loss was 40400 tons carbon / 30 km².
- Urban Area Site 41: initial SOC of. 0.92%, final SOC of 0.00055%, resulting in a SOC change of -0.91945%. The associated carbon loss was 27100 tons carbon / 20 km².

As shown in Table 4, the data unequivocally indicate significant carbon losses in surface soils across all three represented land uses over the past 30 years. Rangelands show the largest *absolute* carbon loss per unit area (40400 tons carbon / 30 km²) and the largest *percentage* decrease in SOC (a staggering ~97.8% reduction from 2.25% to 0.05%). Urban areas also show a substantial percentage loss (~99.9% reduction from 0.92% to 0.00055%), indicating severe degradation of their natural carbon stocks. Agricultural soils, despite showing a smaller percentage loss (~40.6% reduction from 1.75% to 1.04%), still represent a significant release of previously stored carbon.

These quantitative carbon losses directly translate to substantial greenhouse gas ($CO_2$) emissions from the terrestrial ecosystem to the atmosphere. This directly contributes to atmospheric warming and global climate change, counteracting the desired role of soils as carbon sinks. The magnitude of the loss, particularly in rangelands and urban areas, strongly suggests that historical land use conversion and ongoing unsustainable management practices are the primary, if not fundamental, drivers of these emissions within the region. This data underscores the urgent and critical need for immediate interventions to halt and reverse these carbon losses. For rangelands, this implies a desperate need to address overgrazing and implement restorative ecological practices. For urban areas, it highlights the severe and often overlooked impact of urban development on natural soil carbon stocks and the necessity of integrating green infrastructure urban planning that prioritizes soil health and carbon retention. For agricultural areas, despite the relatively lower losses, it emphasizes the importance of adopting and scaling up carbon-sequestering agricultural practices (e.g., conservation agriculture, agroforestry) to prevent further degradation and potentially turn these lands into net carbon sinks. This finding is a direct foundation for climate change mitigation strategies in the region.

**Factors Influencing Carbon Sequestration and Loss**

Several factors contribute to soil carbon dynamics, including soil physicochemical properties, climatic conditions, and land use practices:

**Soil Compaction**: High bulk density and low porosity in urban and rangeland soils can reduce aeration, hindering aerobic microbial activity essential for stable humus formation of organic matter. It can also limit the physical protection of organic matter within soil aggregates, making it more vulnerable to decomposition and erosion.

**Table 4. Soil Organic Carbon Dynamics and Carbon Footprint by Land Use (Surface Soil)**

| Land Use | Initial SOC (%) | Final SOC (%) | SOC Change (%) | Carbon Footprint (tons carbon losses / km²) |
|---|---|---|---|---|
| Agricultural Soil | 1.75 | 1.04 | -0.71 | 20700 / 50 |
| Rangelands | 2.25 | 0.05 | -2.2 | 40400 / 30 |
| Urban Areas | 0.92 | 0.00055 | -0.91945 | 27100 / 20 |

Note: Data derived from for representative surface samples.

**Table 5. Summary of Overall Mean Soil Properties by Land Use (Averages of Surface and Subsurface Depths)**

| Property | Agricultural | Rangelands | Urban Areas |
|---|---|---|---|
| Bulk Density, g/cm³ | 1.46 | 1.54 | 1.54 |
| Sand, % | 58.58 | 68.23 | 44.85 |
| Silt, % | 25.02 | 20.50 | 34.10 |
| Clay, % | 16.40 | 11.20 | 21.05 |
| Porosity, % | 44.82 | 42.06 | 41.74 |
| Water Retention (-10kPa), % | 20.47 | 15.19 | 25.73 |
| Water Retention (-1500kPa), % | 10.45 | 6.97 | 13.18 |
| AW, % | 10.02 | 8.21 | 12.55 |
| Ks, cm/hr | 22.72 | 45.18 | 10.64 |
| pH | 7.72 | 8.24 | 8.32 |
| ECe, dS/m | 1.00 | 1.40 | 1.91 |
| SOC, % | 1.05 | 0.49 | 0.33 |
| OM, % | 1.81 | 0.85 | 0.57 |

| Property | Agricultural | Rangelands | Urban Areas |
|---|---|---|---|
| CEC, cmol/kg | 14.70 | 12.05 | 7.91 |
| $CaCO_3$, % | 7.42 | 9.94 | 12.91 |
| N, ppm | 1500 | 1000 | 600 |
| P, ppm | 14.50 | 9.92 | 6.20 |
| K, ppm | 224.23 | 149.26 | 99.19 |

**Salinity and pH**: High salinity (ECe) levels and alkalinity can create stressful conditions for microbial communities, affecting their metabolic efficiency and overall ability to decompose organic matter and form stable soil aggregates that protect carbon. High calcium carbonate content can also influence organic matter stability and decomposition rates.

**Climatic Conditions**: Elevated temperatures accelerate the rate of organic matter decomposition. Low and erratic precipitation leads to sparse vegetation cover, which in turn reduces fresh organic matter inputs (plant biomass) to the soil. High evapotranspiration exacerbates water stress, limiting plant growth and thus the potential for carbon input into the soil system.

**Land Use Practices**: Agricultural practices involving intensive tillage can expose organic matter to oxidation, leading to carbon loss. Overgrazing in rangelands reduces vegetation cover and root biomass, leading to decreased carbon inputs and increased soil susceptibility to erosion, which carries away carbon-rich topsoil. Urbanization, involving extensive excavation, surface sealing, and removal of natural topsoil, directly releases vast amounts of carbon and prevents future carbon sequestration in affected areas.

## 5. Interconnectivity and Impacts: A Holistic Perspective

This section integrates the detailed analyses of physical, chemical, and climatic data, demonstrating the complex interconnections and feedback loops governing soil health and carbon dynamics in the El Hammam region.

### Land Use as a Central Driver

**Agricultural Soils:** Despite human intervention, generally exhibit relatively better physical properties (e.g., lower bulk density, higher porosity, moderate saturated hydraulic conductivity) and chemical properties (e.g., higher SOC, OM, CEC, and nutrient levels) compared to other land uses (Ahmed et al., 2023). This is likely attributable to active management practices and deliberate organic inputs. However, they still show notable salinity and, crucially, a measurable loss of soil carbon over the past 30 years.

**Rangelands:** Characterized by sandy texture, high hydraulic conductivity but low water retention, low SOC, low CEC, and depleted nutrient levels (Ahmed et al., 2023). These inherent characteristics are exacerbated by overgrazing (Ahmed et al., 2023) and harsh arid conditions, leading to significant carbon losses and increased susceptibility to wind and water erosion.

**Urban Areas:** Exhibit a distinct loamy texture but are severely compacted (evidenced by high bulk density, low porosity, and very low saturated hydraulic conductivity). They are also highly saline and critically depleted in SOC, OM, and essential nutrients. This reflects the intense anthropogenic disturbance, surface sealing, and removal of natural topsoil associated with urban development, leading to the most severe recorded carbon losses.

### Climate Change Amplifying Degradation

The observed warming trend (increasing maximum and minimum temperatures) and consistently high reference evapotranspiration rates intensify water stress and existing salinization processes across all land uses. This is particularly detrimental in already vulnerable rangelands and urban areas. The low and erratic precipitation patterns, coupled with significant wind speeds, heighten erosion risks, especially in bare or poorly vegetated areas. This leads to further loss of fertile topsoil, organic matter, and associated carbon, creating a cycle of degradation. The analysis demonstrates concurrent trends: rising temperatures, high reference evapotranspiration, and low, erratic precipitation alongside the prevalence of high ECe, critically low SOC, and documented carbon losses. There is a strong and detrimental interplay between climate change and soil degradation in the El Hammam region, where each process reinforces the other. A warmer climate leads to increased evapotranspiration, intensifying water deficit and salinization. This water stress and salt toxicity reduce natural vegetation cover and productivity (inferred from land use impacts by Ahmed et al., 2023), which in turn diminishes organic matter inputs to the soil, leading to declining SOC levels. Reduced SOC further degrades soil structure, making it more susceptible to compaction and erosion, thereby reducing its capacity to retain water and nutrients. This further increases the soil's vulnerability to climatic stress, perpetuating a cycle of degradation. These positive feedback loops result in accelerated soil degradation, reduced carbon sequestration capacity, and increased greenhouse gas emissions, diminishing the overall ecosystem's resilience to climate change.

**6. Spatial Distribution Maps of Soil Properties**

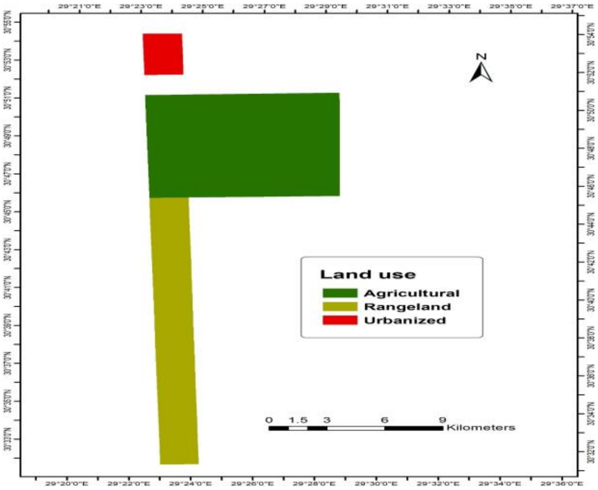


**Fig. 3. Study Area Land Use**

Figure 3 illustrates the distribution of the main land use types in the studied area, namely agricultural land, rangeland, and urban areas. This figure clearly shows the geographical ranges of each land use type, providing a visual context for the results discussed in the research. Agricultural areas occupy a large area in the center and south of the region, while rangelands are located in the longitudinal strip and urban areas in the north.

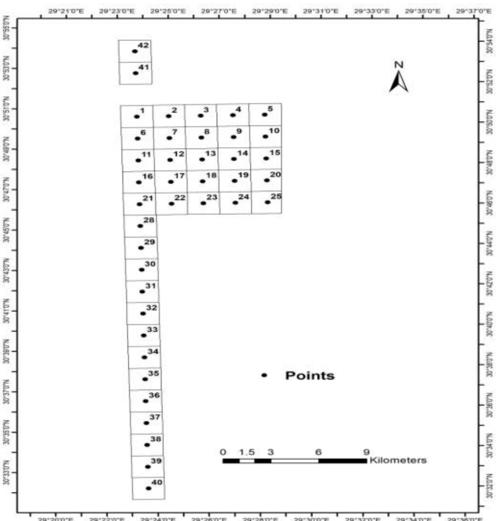


**Fig. 4. Soil Sampling Points in El Hammam Region**

This Figure4 shows the exact locations of the sampling points (50 points) scattered throughout the study area. The map illustrates the systematic distribution of these points across the grid, ensuring comprehensive representation of all different land use types (agricultural, rangeland, urban). This systematic distribution is crucial to ensure the accuracy of the spatial analysis and its reliable results.

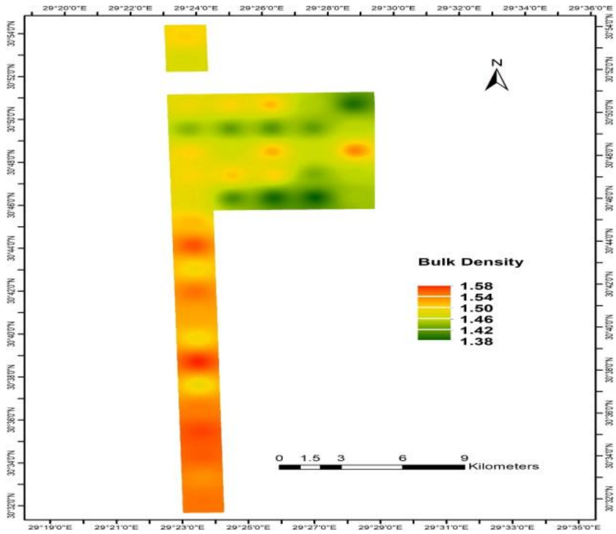


**Fig. 5. Spatial Distribution of Bulk Density in Soils**

Figure (5) indicates the spatial distribution of bulk density for soils. The areas with high bulk density (red and orange) revealed the increase in soil compaction, which is clearly visible in rangeland and urban areas. In contrast, agricultural land shows lower values, indicating an improvement in soil structure as a result of agricultural practices.

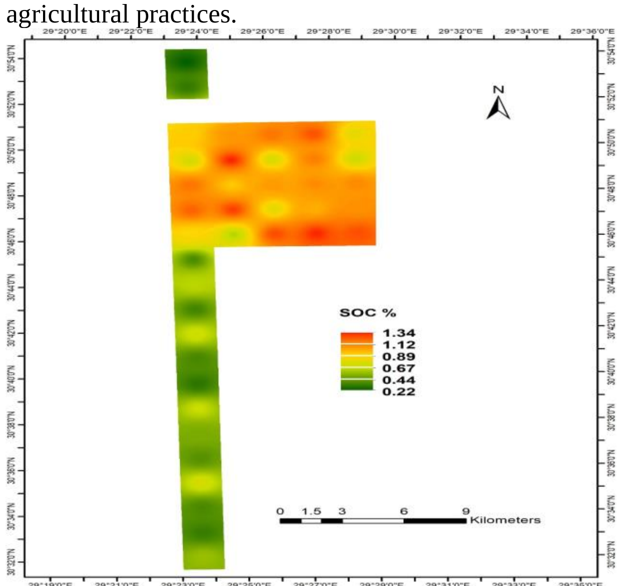


**Fig. 6. Soil Organic Carbon (SOC) Distribution in Soils**

The Figure (6) shows the spatial distribution of soil organic carbon (SOC). It can be seen that the highest values (red and orange areas) are concentrated in agricultural land, confirming that agricultural practices contribute to carbon sequestration. In contrast, low carbon values (green areas) appear in rangeland and urban areas, indicating severe degradation and significant carbon loss in these lands.

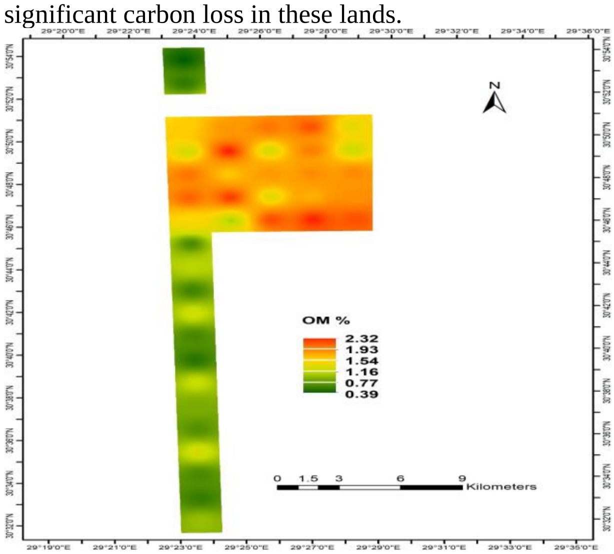


**Fig. 7. The Spatial Distribution of Soil Organic Matter in Soils**

The spatial distribution of organic matter (OM) in the soils indicated that the close relationship between organic matter and organic carbon, this distribution follows a similar pattern to the organic carbon, showing the highest concentrations of organic matter in agricultural land and the lowest in rangeland and urban areas. This confirms that organic matter is a key indicator of soil health in the region, Fig. (7).

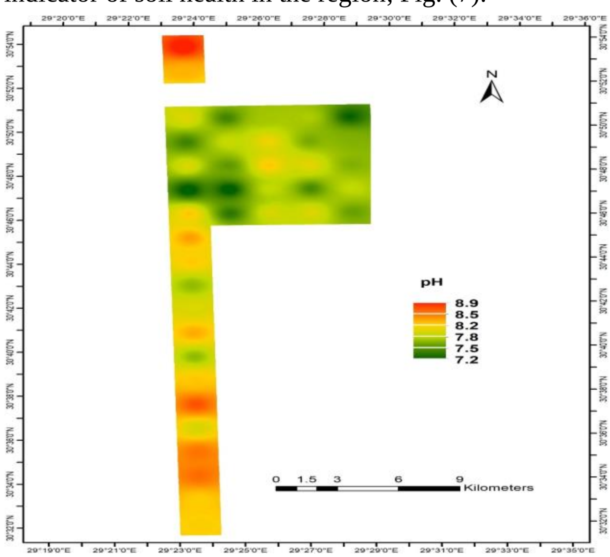


**Fig. 8. The Spatial Distribution of pH in Soils**

The pH values in the region range from neutral to alkaline (above 7.0). Areas marked in orange and red (higher pH values) are more prevalent in rangeland and urban lands, indicating increased soil alkalinity, a characteristic common in arid and semi-arid regions, Fig. (8).

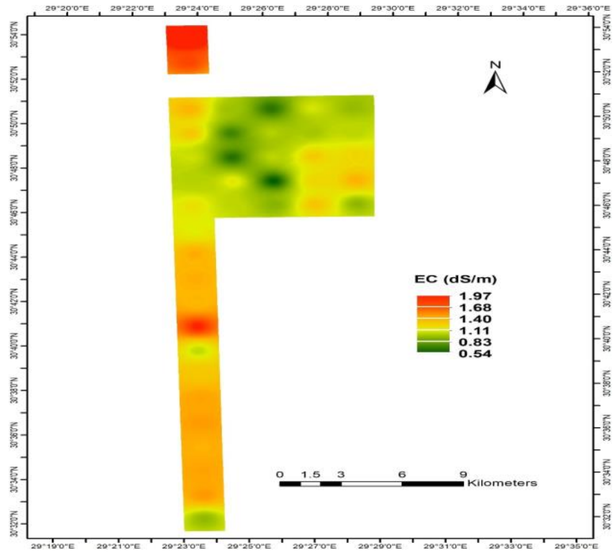


**Fig. 9. The Spatial Distribution of the electric conductivity, ECe, in Soils**

The areas with high salinity (red and orange) appear in urban areas and pastures, confirming that these lands suffer from significant salinization. In contrast, agricultural lands show lower salinity values (green and yellow), suggesting that agricultural practices may help control salinity compared to other land types, Fig.9.

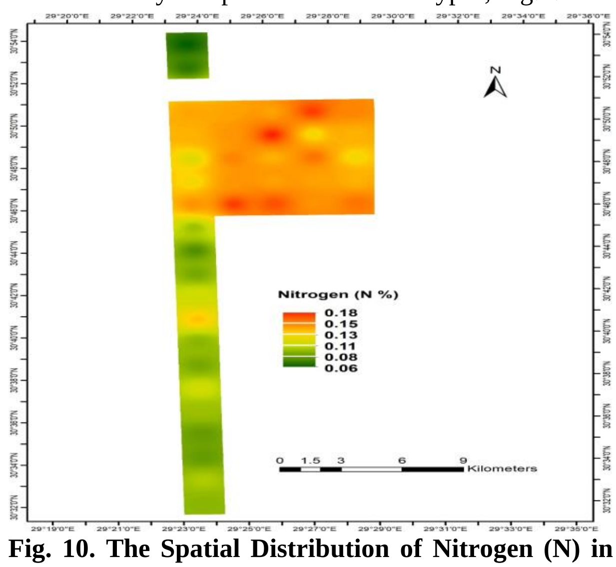


**Fig. 10. The Spatial Distribution of Nitrogen (N) in soils**

Figure 10 shows the spatial distribution of nitrogen concentration in the soils. Agricultural lands (red and orange areas) have the highest nitrogen levels, likely due to the addition of fertilizers and other agricultural practices that increase soil fertility. In contrast, grasslands and urban areas show low nitrogen levels, indicating nutrient depletion in these ecosystems.

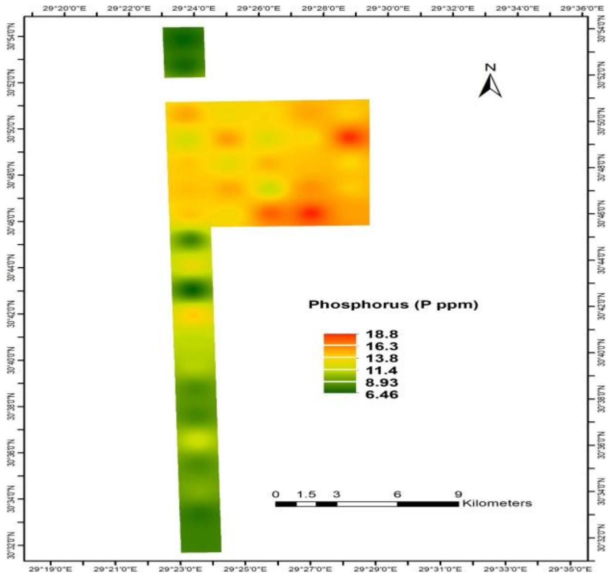


**Fig. 11. The Spatial Distribution of Phosphorus (P) in soils**

The spatial distribution of phosphorus in the soils shows that the agricultural land (red and orange areas) is the highest values of phosphorus, Fig. 11. These values are reflecting the use of phosphate fertilizers to improve soil fertility and support crop growth. Rangeland and urban areas show low levels of phosphorus, reflecting the poverty of these soils in this important nutrient.

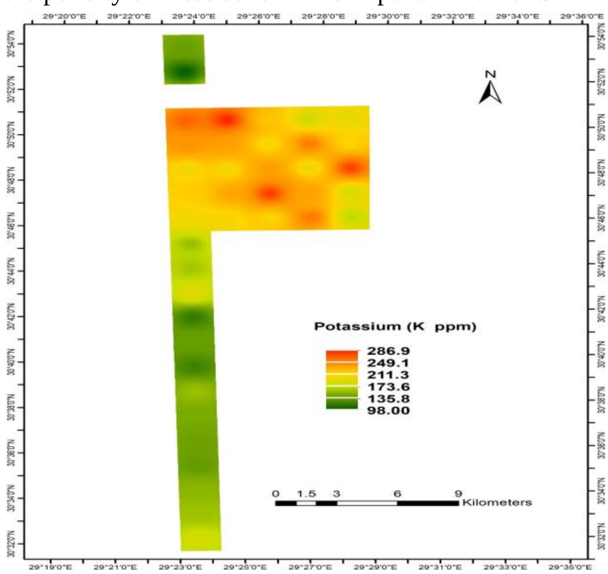


**Fig. 12. The Spatial Distribution of Potassium in soils**

Fig. 12 shows the spatial distribution of potassium in the soils. This distribution is consistent with other nutrient distributions, with agricultural land (red and orange areas) showing the highest potassium levels. This strong correlation between potassium levels and land use type underscores the key role of management practices in determining soil fertility and nutrient concentrations.

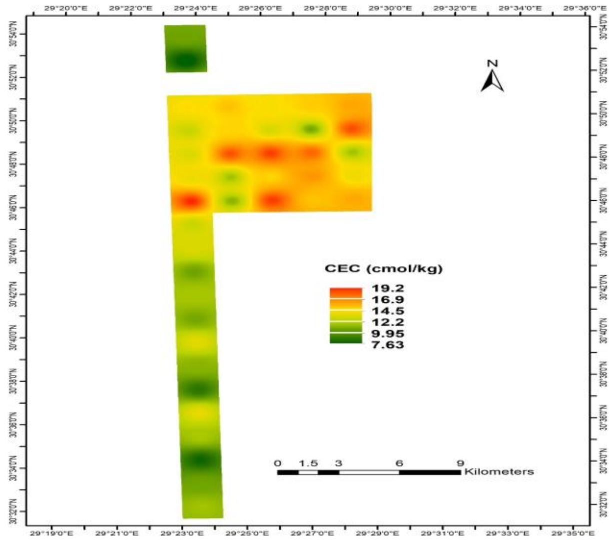


**Fig. 13. The Spatial Distribution of Cation Exchange Capacity (CEC) for Soils**

The spatial distribution of cation exchange capacity (CEC) in soils corresponds with the results for organic carbon and organic matter, with the highest values appearing in agricultural lands (red and orange areas), Fig. 13. This confirms that the reduction in organic matter in rangeland and urban areas is the main factor behind the reduced capacity of these soils to retain cations and nutrients.

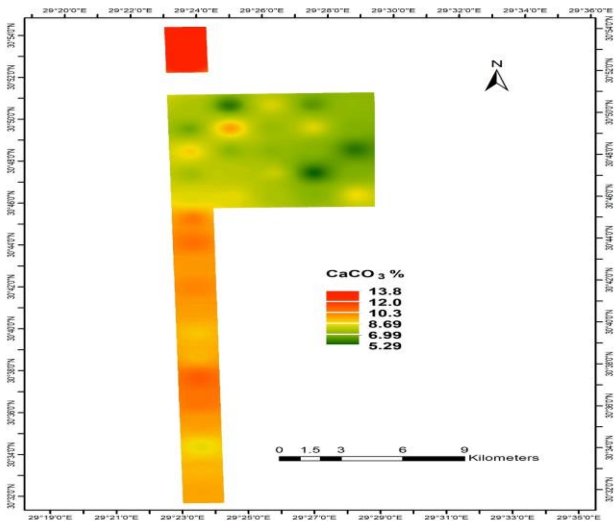


**Fig. 14. The Spatial Distribution of Calcium Carbonate ($CaCO_3$) for soils**

The spatial distribution of calcium carbonate (CaCO3) values in soils show that the highest percentage of calcium carbonate are found in urban areas and rangeland (in orange and red), Fig. 14. These high levels of calcium carbonate contribute to increased soil alkalinity and negatively affect the availability of certain micronutrients, which impacts plant growth.

## CONCLUSIONS AND RECOMMENDATIONS

This study provides a comprehensive analysis of soil physicochemical properties, climatic data, and soil carbon footprint assessment in the El Hammam region of Egypt. The findings clearly indicate that the region's soils are under significant stress from both climate change and human activities, leading to widespread degradation and substantial loss of stored carbon.

**Soil Property Variation by Land Use:** Agricultural soils exhibit relatively better characteristics, while rangelands and urban areas show significant degradation in both physical (e.g., compaction) and chemical (e.g., salinity, low SOC, nutrient depletion) properties.

**Climatic Exacerbation:** The region experiences a clear warming trend, consistently high reference evapotranspiration rates, and low, erratic precipitation. These harsh climatic conditions intensify water stress, soil salinization, and erosion risks, diminishing soil resilience.

**Significant Carbon Losses:** Soil carbon footprint data indicates that soils in the El Hammam region are a net source of carbon emissions, with all land uses showing substantial losses of stored organic carbon over the past three decades. Rangelands and urban areas are the most severely affected, highlighting the devastating impacts of overgrazing and urbanization on soil carbon stocks.

**Negative Feedback Loops:** A detrimental interplay exists between climate change and soil degradation. Warming accelerates organic matter decomposition and increases salinization, while soil degradation reduces its carbon sequestration capacity, contributing to further greenhouse gas emissions.

**Recommendations for Climate Change Mitigation and Soil Management:**

Based on the findings, the following recommendations are put forth to enhance sustainable soil management and climate change mitigation in the El Hammam region:

1. **Promote Conservation Agriculture Practices:** In agricultural soils, practices such as no-tillage, cover cropping, crop rotation, and organic matter additions (e.g., compost) should be encouraged and scaled up. These practices will help increase SOC, improve soil structure, enhance water retention, reduce the need for synthetic fertilizers, and promote carbon sequestration (Peralta et al., 2022).
2. **Integrated Rangeland Management:** To combat overgrazing and erosion in rangelands, rotational or intensive grazing systems, determination of carrying capacity, and promotion of drought-tolerant and soil-improving plant species should be implemented. These measures will help restore vegetation cover, increase organic matter inputs, and reduce soil erosion, thereby improving carbon stocks and soil water holding capacity (Lal, 2020).
3. **Sustainable Urban Planning and Development:** In urban areas, the development of green infrastructure, including parks, green spaces, and permeable surfaces, should be prioritized. Construction plans should incorporate techniques to minimize soil compaction, preserve topsoil, and utilize reclaimed soils rich in organic matter. This will help restore soil functions, reduce runoff, and enhance carbon sequestration in urban environments).
4. **Efficient Water Management:** Given the chronic water deficit in the region, efficient water management is crucial. This includes adopting water-saving irrigation techniques (e.g., drip irrigation), utilizing treated wastewater, and developing drought- and salt-tolerant crop varieties. These strategies will reduce water stress on soils and plants and mitigate the exacerbation of salinization (Peralta et al., 2022).
5. **Continuous Monitoring and Research:** Long-term monitoring programs for soil properties, carbon dynamics, and climatic data should be established to assess the effectiveness of management strategies and adapt to changing conditions. Future studies incorporating GIS mapping and remote sensing data are essential to identify vulnerable areas and guide targeted interventions more precisely (Zhang et al., 2020).

By implementing these integrated recommendations, the El Hammam region can enhance its soil resilience to climate change, reduce greenhouse gas emissions, and sustain its ecosystem productivity in the long term.

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## الملخص العربي

# آثار تغير المناخ على التباين المكانى فى الخصائص الفيزيوكيميائية للتربة تحت نظم استخدام متنوع للأراضى فى منطقة الحمام، شمال مصر

سحر محمد إسماعيل

التربة هي مكون حيوي من النظام البيئي للأرض، حيث تلعب دورًا محوريًا في تنظيم المناخ من خلال وظائفها في دورات الكربون والنيتروجين والعمليات الهيدرولوجية (منظمة الأغذية والزراعة، ٢٠٢٢). ومع ذلك، تواجه أنظمة التربة تهديدات متزايدة من الضغوط المزدوجة لتغير المناخ والأنشطة البشرية، مما يعرض قدرتها على توفير خدمات النظام البيئي الأساسية للخطر. تركز هذه الدراسة على منطقة الحمام شبه القاحلة في مصر لتقديم تحليل شامل للخصائص الفيزيائية والكيميائية للتربة عبر الاستخدامات المختلفة للأراضي (الزراعية، المراعي، والمناطق الحضرية)، وتقييم الاتجاهات المناخية، وحساب البصمة الكربونية للتربة.

كشفت النتائج عن اختلافات كبيرة في خصائص التربة بناءً على استخدام الأرض والعمق. أظهرت التربة الزراعية خصائص فيزيائية وكيميائية أفضل نسبيًا، بما في ذلك انخفاض الكثافة الظاهرية، وارتفاع المسامية، وزيادة محتوى الكربون العضوي والمغذيات، على الرغم من أنها ما زالت تعاني من بعض الملوحة وفقدان ملحوظ للكربون على مدار العقود الثلاثة الماضية. في المقابل، أظهرت تربة المراعي والمناطق الحضرية علامات حادة للتدهور، وتتميز بارتفاع الكثافة الظاهرية، وانخفاض المسامية، وارتفاع الملوحة، واستنزاف حرج للكربون العضوي والمغذيات. كانت البصمة الكربونية للتربة سلبية بشكل كبير في جميع استخدامات الأراضي، مما يشير إلى خسارة كبيرة في الكربون المخزن، خاصة في المراعي والمناطق الحضرية، مما يجعل التربة مصدرًا لانبعاثات غازات الاحتباس الحراري بدلاً من كونها بالوعة كربون.

أكدت البيانات المناخية للفترة ١٩٩١–٢٠٢١ وجود اتجاه واضح للاحترار (زيادة في درجات الحرارة القصوى والدنيا) ومعدلات تبخر– نتح مرجعي عالية باستمرار، مصحوبة بانخفاض وهطول أمطار متقطع. هذه الظروف المناخية القاسية تزيد من تفاقم تدهور التربة، مما يؤدي إلى تكثيف الإجهاد المائي، والملوحة، ومخاطر التعرية. تسلط هذه التفاعلات الضوء على حلقات التغذية الراجعة الإيجابية الحرجة بين تغير المناخ وتدهور التربة في المنطقة.

تؤكد هذه النتائج على الحاجة الملحة لاستراتيجيات مستدامة ومصممة خصيصًا لإدارة التربة. تشمل التوصيات تعزيز ممارسات الزراعة المحافظة لتعزيز عزل الكربون في الأراضي الزراعية، وتطبيق إدارة المراعي المتكاملة لمكافحة الرعي الجائر والتعرية، ونشر حلول البنية التحتية الخضراء في المناطق الحضرية لاستعادة صحة التربة وقدرتها على تخزين الكربون. تعتبر الإدارة الفعالة للمياه وتطوير أصناف المحاصيل المقاومة للملوحة والجفاف أمرًا بالغ الأهمية أيضًا لتعزيز مرونة المنطقة في مواجهة تغير المناخ.

**الكلمات الدالة:** خصائص التربة، تغير المناخ، استخدام الأراضي، عزل الكربون، إدارة التربة، خرائط نظم المعلومات الجغرافية.