Blueprint Academic Publishers

Journal of Aquatic and Terrestrial Ecosystems
3(2)
Received: April 20, 2025
Accepted: June 15, 2025
Published: June 30, 2025

Seasonal Climate Variability Influence on Soil Characteristics Along Disturbance Gradient in King'wal Wetland, Kenya

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Abstract

Soil plays a crucial role in supporting plant growth and development in inland wetland ecosystems. However, soil characteristics are sensitive to seasonal climate variability and anthropogenic disturbances, which influence their ecosystem services and the overall health status. This study investigated how these factors influence soil properties in King'wal Wetland, a vital ecosystem in Kenya experiencing increasing human pressure. Data on rainfall and temperature from September 2021 to August 2022 were obtained from the Kenya Meteorological Department, Kapsabet. Four study sites were selected and stratified into the least disturbed and most disturbed. Four composite soil samples were collected in triplicate using a soil auger from 0 - 10 cm depth below the soil surface at four selected study sites, mixed in a bucket, and placed in a zip-lock labelled bag. The soil samples were transported to the laboratory for analysis of soil pH, organic carbon, moisture, total nitrogen, and phosphorus. The results showed that soil pH and soil phosphorus had higher values in the wet season, but were not significant. Soil moisture varied significantly between wet and dry seasons ($F = 59.2$, $P < 0.001$), organic carbon ($F = 17.7$; $P < 0.001$), and total nitrogen ($F = 31.0$; $P < 0.001$). Furthermore, disturbance influenced all soil characteristics significantly except for total phosphorus. Soil moisture, organic carbon, and total nitrogen concentrations were higher in the least disturbed sites. Soil characteristics were influenced by rainfall, water depth, and air temperature. Water depth and rainfall had a strong positive relationship with soil moisture ($R = 0.21$, $P < 0.01$) and ($R = 0.26$, $P < 0.001$), respectively. However, water depth had a significant negative influence on organic carbon ($R = -0.28$, $P < 0.001$) and total nitrogen ($R = -0.23$, $P < 0.001$). Furthermore, temperature had a significant negative relationship with soil moisture ($R = -0.41$; $P < 0.001$) and water depth ($R = -0.66$; $P < 0.001$) in King'wal wetland. Understanding the influence of seasonal climatic changes and human-induced disturbances on wetland soil characteristics are crucial. This will inform managers and scientists to restore and

conserve wetland soil as part of nature-based solutions for the effects of climate variability and change.

Keywords: Soil organic carbon, nutrients, air temperature, rainfall, inland wetland, Kenya

Journal ISSN: 2960-1118

Issue DOI: https://doi.org/10.69897/jatems.v3i2

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Funding: The author received no financial support for the research, authorship and/or publication of this article.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials or upon reasonable request.

Competing interests: The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Introduction

Climate variability is particularly affecting inland wetland ecosystems due to global climate change occurring at an accelerated pace (IPCC, 2023). Africa is vulnerable to seasonal climate variability due to an increase in temperature from 3 °C to 4 °C by the end of the 21st Century (IPCC, 2019). These changes have led to frequent droughts and floods, leading to damage to ecosystems and human livelihoods (Tan et al., 2020). Seasonal changes in rainfall and temperature affect wetland hydrology, which in turn influence the status of wetland soil supporting plant distribution (Leemhuis et al., 2016). Currently, studies have shown that rainfall and temperature variabilities are experienced in East Africa and Kenya has not been left out (Ayugi et al., 2016; Palmer, et al., 2023). Therefore, there is a need to understand how seasonal climate variability influences wetland soil characteristics and, in turn, affects the quantity and quality of ecosystem services. This will assist managers and policymakers in coming up with climate adaptation strategies for the local ecosystems (Martens, et al., 2021).

Inland freshwater wetlands are crucial for providing habitats for diverse organisms and for regulating biogeochemical cycles (Mitsch & Gosselink, 2015). These ecosystems are characterized by hydric soil that supports a variety of organisms, which play essential roles in inland wetlands. Such roles include, but are not limited to, breaking down organic matter and releasing nutrients that plants absorb for their growth (RCS, 2018). The macrophytes supported by the soil are habitats for various organisms, hence referred to as a hotspot for biodiversity (Lynch et al., 2024; He et al., 2021). Furthermore, soil characteristics interact to modify the prevailing conditions at the locality and lead to either loss or enhancement of nutrient concentrations. According to Saaltink et al. (2018), hydrology and soil type influence nutrient

availability in plants. Moreover, temperature increase enhances decomposition of organic material and may alter the potential of the wetland to sequester carbon (Ma et al., 2025).

Although inland wetland soils are important resources, they are threatened by seasonal climate variability and anthropogenic activities. These threats drive changes in soil characteristics in inland wetlands and increase the rate at which they are destroyed, leading to a loss of soil function. For example, climate variability in the form of wet and dry conditions influences the change observed in the variation of nutrient concentration, which affects plant productivity (Ding et al., 2025). Climate variability in Kenya has disrupted many of the economic, social, and ecological sectors (WEF, 2020). This has occurred as a result of changes in the global temperatures as well as land use and land cover changes in the region (Gichangi et al., 2015). Examining the response of soil characteristics to seasonal climate changes would assist the managers and other stakeholders in understanding how season and human activities disrupt wetland resources and their ecosystem services, serving as an early warning.

King'wal wetland, a crucial inland wetland in the region, is particularly influenced by prevailing seasonality and faces increasing anthropogenic pressure due to surrounding human activities. This wetland is surrounded by intensive human activities such as agriculture, infrastructure development, and settlement, making them sensitive to minor disturbances from seasonality and human impact, which influence plant productivity (Rongoei et al., 2023). Seasonal climate variability interacts with human disturbances to worsen changes observed in wetland soil characteristics. The dry and wet conditions influence the prevailing seasonality in the region and affect the status of the wetland soil. Important soil characteristics assessed in King'wal wetland were soil moisture, pH, organic carbon, total phosphorus, and nitrogen. These characteristics are important for the growth and development of macrophytes, which determine their composition, distribution, and diversity in the wetland (Dodkins et al., 2012). However, hydrological characteristics such as water depth and movement influence soil quality, and in turn influence macrophytes (Baláži & Hrivnák, 2017).

Threat to King'wal wetland due to interaction between seasonal climate changes and human-induced disturbances has disrupted the ecosystem's function as a habitat for Sitatunga (endemic to the region) (Sitienei et al., 2012) and the conservation of biodiversity in wetlands. Furthermore, changing wetland conditions will affect birds and reduce their populations, particularly the Grey Crown Crane (*Bulaera regulorum*) (BirdLife International, 2020; KWS, 2025). According to Rodwell & Morrison (2020), this bird is a good indicator of a healthy wetland. Apart from King'wal wetland, which is one of the conservation sites of Grey Crowned Crane, other inland wetlands have been identified in Kenya and include Kipsaina, Sio Siteko, and Lake Ol Bolossat (KWS, 2025). The conservation of these sites will protect other species, hence enhancing biodiversity. Therefore, King'wal wetland is a representative of the inland wetlands within the Lake Victoria North Basin and is influenced by climate variability. It also faces threats such as the eutrophication affecting Lake Victoria, shared by several countries for fish resources and transportation of goods among the East African nations.

Studies conducted in King'wal wetland mainly focus on water quality and socio-economic aspects, which help understand the community's perceptions and what they have lost in the ecosystem (Mule et al., 2015; Momanyi & Ariya, 2015). However, wetland soil characteristics have not been studied in King'wal wetland, which is being influenced

by seasonal climate variability and anthropogenic disturbances. Changes in the climate will disrupt soil characteristics, which in turn affect the growth of macrophytes supporting diverse organisms and loss of soil fertility, hence may not support the livelihoods of surrounding communities. Determining the link between soil characteristics, season, and disturbances caused by human activities is crucial to protect the remaining wetland areas from intensive destructive activities, particularly in the context of climate change being experienced globally. This study hypothesized that soil characteristics varied with seasons and disturbance gradients in the wetland. This implies that a shift in soil characteristics (nutrients, pH, moisture, and organic carbon) would occur when the seasonal conditions prevail in the wetland. The interaction of seasonal climate variability and anthropogenic disturbances will influence the health of the wetland soil, affecting the functioning (e.g. biogeochemical cycles, climate regulation, and water purification) of inland wetlands. However, the link between soil characteristics, seasonal climate variability, and human disturbances has not been studied in King'wal wetland. This information will form the basis for the Nandi County government and other government departments to manage and restore wetlands in the context of global climate change.

This study was based on the following objectives: (1) To investigate how soil properties (soil moisture, pH, soil organic carbon, total phosphorus, and nitrogen) varied with season, (2) To assess the characteristics of wetland soil along disturbance gradient, (3) To determine the relationship between climate variables (rainfall, water depth, and temperature) and soil characteristics in King'wal wetland and their interactions. The study will add knowledge and provide meaningful insights toward the sustainable management of wetland ecosystems in the context of global climate change.

Methodology

Study area

King'wal wetland is a riverine ecosystem found along the King'wal river that joins Kimondi and later to Yala Swamp, which is the biggest wetland in Lake Victoria. It is located at 1946 m above sea level and lies between latitudes 35°08'34.1" East to 35°11'22.0" East and longitudes 0°15'11.3" North to 0°16'13.6" South (Figure 1).

The wetland covers an area of 2.73 km^2 (MEMR., 2012). The temperature varies between 18 to 25 °C while rainfall varies between 1600- and 2000 mm per annum with a bimodal mode of rainfall. The long rainy season occurs in March, April, May, and June (MAMJ) while short rains are experienced in July, August, September, and October (JASO). This wetland is an important habitat for several organisms, including Sitatunga (*Tragelaphus spekii),* diverse birds, and fish species (CGN, 2018).

Sampling Site and Field Survey

The wetland was stratified into two: least disturbed (LD) and most disturbed (MD) sites. The stratification was based on the presence or absence of human activities influencing wetland vegetation. Most disturbed sites had more than two human activities. The activities included conversion of the wetland to cropland, clearing and burning of wetland vegetation, growing exotic tree species like *Eucalyptus* spp., and livestock grazing during the dry season. However, in the least disturbed sites, grass harvesting for hut thatching was done in the dry season (Rongoei et al., 2023).

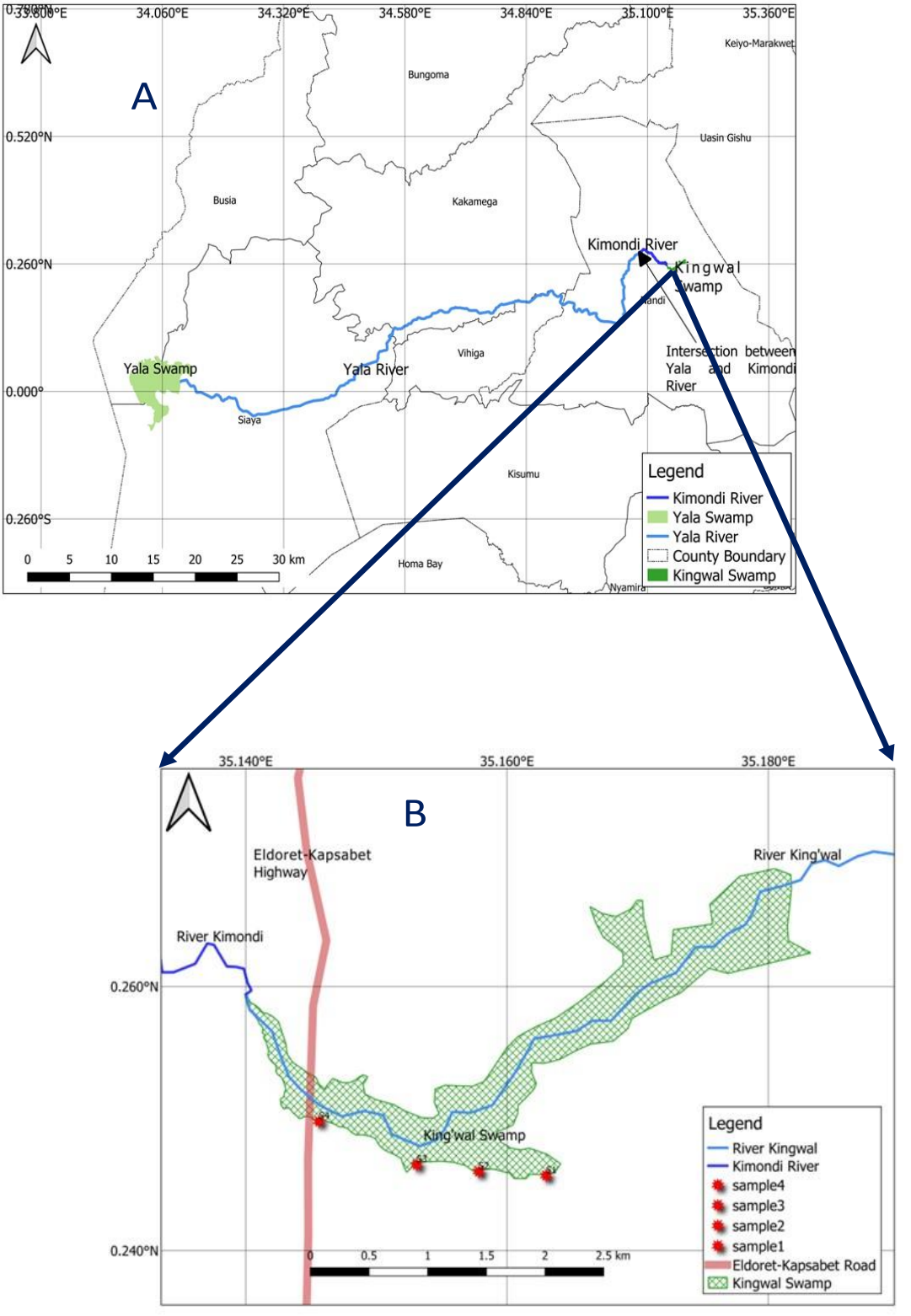

Figure 1: Map showing the location of King'wal wetland connected with Yala swamp by Kimondi river in the east and Yala river in the west (A), King'wal riverine wetland showing sampling points in red dots (S1, S2, S3, and S4) (B). (Map drawn by M.R. Kimurgor)

King'wal wetland vegetation zonation from the dry upland edge of the wetland had a strip of *Eucalyptus* spp. Followed by dominant grass with patches of herbs. This was followed by a mixture of reeds towards a moist soil with the presence of reeds and *Cyperus esculentus* L. zone. At the edge of permanently inundated areas was dominated by a mixture of moist-loving plants, including *Hydrocodyles* spp., *Sphaeranthus* spp., and *Cyperus difformis*. Finally, the area with permanently inundated soil throughout the study period was covered by *Cyperus papyrus* L. (papyrus zone). They formed thick mats at the edges of the river.

The study was conducted in one year between September 2021 to August 2022. Rainfall and temperature data were obtained from the Kenya Meteorological Department in Kapsabet. This data was used to determine the relationship between climate variables and soil properties along the disturbed gradient. From each study site (least disturbed and most disturbed), monthly water depth was measured using a graduated meter-ruler in the field, and data were recorded in a field notebook. Three soil samples were collected from 1 m^2 quadrats using an auger driven to a depth of 10 cm below the soil surface in a V-shaped manner. Twelve soil samples collected from the first row of quadrats formed the first composite soil sample, which was mixed in a bucket (Figure 2). The second row formed the second composite soil sample, and the third row formed the third composite sample, giving a total of 36 soil samples per site. Sampling of soil was from South to North towards the river (Figure 2).

The soil samples for soil moisture content were placed in well-labelled pre-weight cans, closed, and placed in a cool box with ice. Another sub-sample of about 500 g of soil was placed in well-labelled zip-lock bags. These samples were used to analyse the physical and chemical properties of soil, such as soil pH, soil organic carbon (SOC), soil total nitrogen (STN), and soil total phosphorus (STP). The samples were transported to the soil laboratory at Egerton University for further processing.

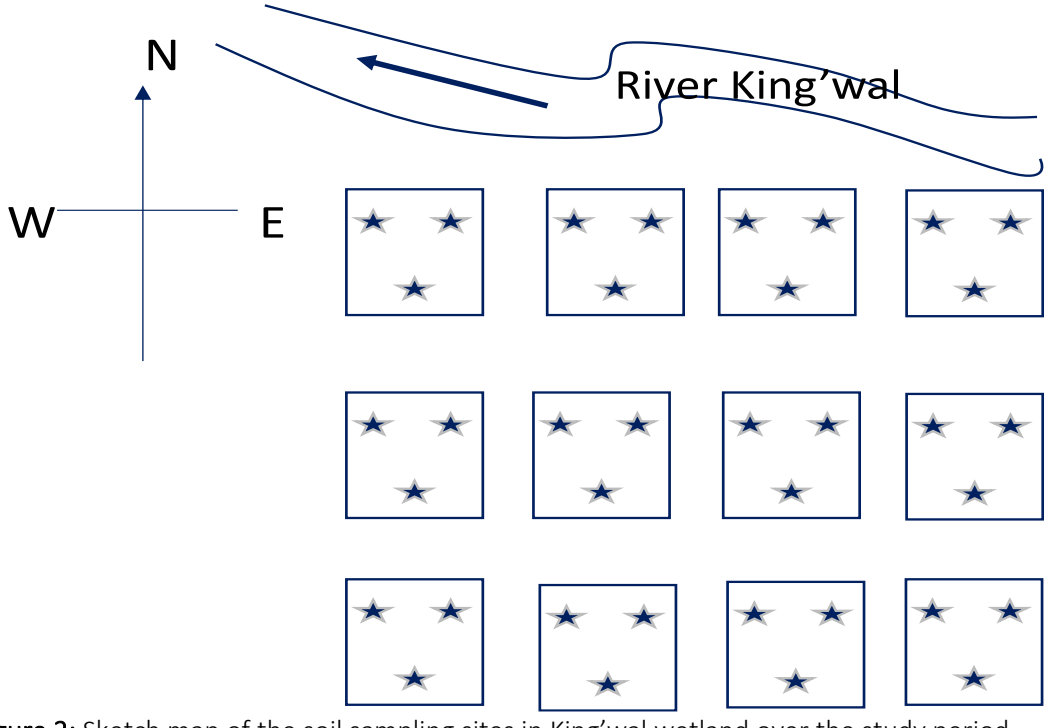

Figure 2: Sketch map of the soil sampling sites in King'wal wetland over the study period

Analysis of soil samples

The soil samples were spread on foil paper and dried at room temperature for at least 10 days. Plant materials present in the soil were removed during drying. The soil was crushed into small particles and passed through a 200 µm sieve and placed in well-labelled small bags to await analysis for STP, STN, SOC, and pH.

For pH analysis, the ratio of soil and water (1:2.5) was placed in a container that was shaken for 30 minutes (Jackson, 1967; RARC & JICA, 2014). After settling, pH measurements were taken using the Sanxin MP512 Precision pH meter model.

To analyze SOC, the Walkley-Black titration method (Walkley & Black, 1934) was used. Soil total phosphorus was determined by the use of a colorimetric method (Okalebo et al., 2002). On the other hand, TN was determined using a Kjeltec auto-distillation device after the digestion of the soil samples (RARC & JICA, 2014; Ryan et al., 2001).

Statistical analysis

The normal distribution was determined using the Shapiro-Wilk Test. Those that did not meet normal distribution were analysed using the Kruskal-Wallis Test. For normally distributed data, One-way ANOVA was used to compare soil properties between seasons (wet versus dry) and between disturbance gradients (least disturbed versus most disturbed) separately. Furthermore, Two-way ANOVA was used to check for interaction between seasons (wet and dry) and disturbance gradients (least disturbed versus most disturbed). Pearson's correlation matrix was used to understand the relationship between climate variables and soil characteristics. The differences between variables were considered significant when $P < 0.05$. All statistical analyses were done using R software version 4.2.2. (R Core, 2022).

Results

Seasonal variation in soil characteristics

Seasonality influenced soil characteristics in the wetland over the study period (Figure 3). Soil moisture varied in King'wal wetland with a mean and standard deviation of 60.8 % ± 15 % and 74.4 % ± 16.1 % in the dry and wet seasons, respectively (Figure 3a). One-way ANOVA showed a significant variation between seasons ($F = 59.2$, $P < 0.001$). On the other hand, soil pH did not vary with season, although there was a slight increase in the wet season, with a mean of 5.70 ± 0.70 and 5.63 ± 0.72, respectively (Figure 3b). Seasonal variation in soil pH was not significant ($F = 0.5$, $P > 0.05$). Furthermore, organic carbon was higher in the dry season than in the wet season, with a mean of 3.40 ± 1.1 % and 2.77 ± 1.2 %, respectively (Figure 3c). The one-way ANOVA showed a significant variation in soil organic carbon between the dry and wet seasons ($F = 15.7$, $P < 0.001$).

Nutrients in the wetland showed variations in the wet and dry seasons. Total phosphorus concentration (STP) in the wetland soil was slightly higher in the wet season, with a mean of 985 ± 483 mg/Kg, and slightly lower in the dry season at 965 ± 507 mg/Kg (Figure 3d). However, in One-Way ANOVA, seasonal variation of STP was not significant ($F = 0.1$, $P > 0.05$). Likewise, total nitrogen concentration (STN) in wetland soil varied between wet and dry seasons. The dry season had a mean of 58.1 ± 45 mg/Kg while the wet season had a mean of 32.1 ± 24.3 mg/Kg (Figure 3e). The seasonal variation in STN was significant (One-Way ANOVA; $F = 31$; $P < 0.001$).

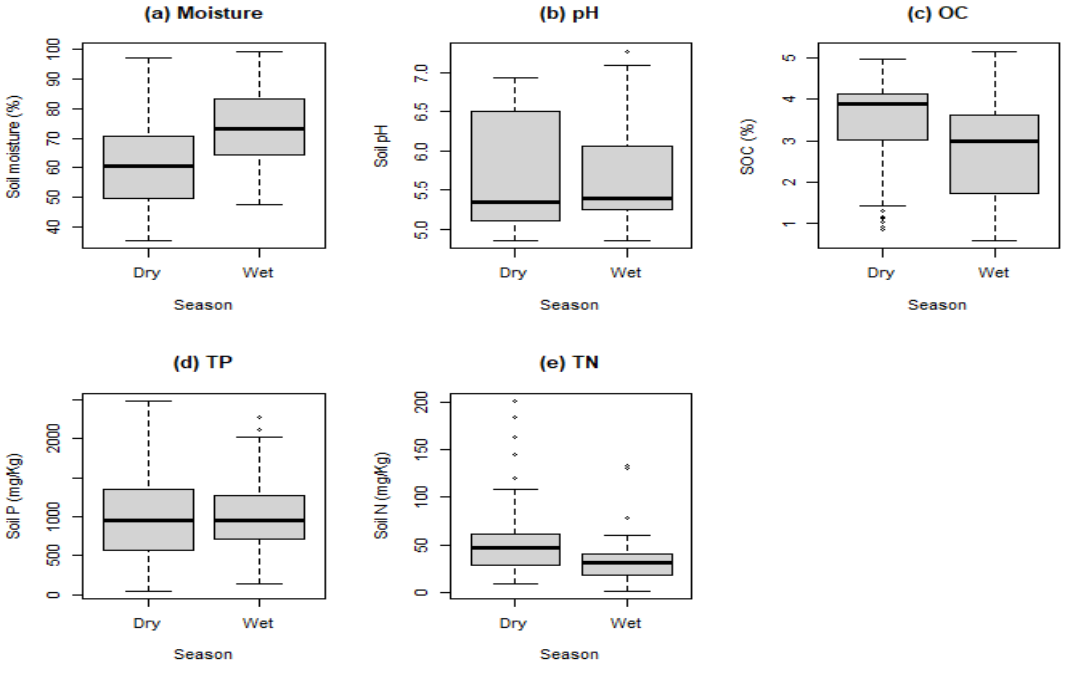

Figure 3: Seasonal variations in soil characteristics (a) moisture; (b) pH; (c) soil organic carbon (OC); (d) Total phosphorus (TP); (e) Total nitrogen (TN) in King'wal wetland

Variation of Soil characteristics along a disturbance gradient

In King'wal wetland, the percent soil moisture content was higher in the LD than in MD sites, with a mean of 73.4 ± 16.1 % and 61.8 ± 11.9 %, respectively (Table 1). A summary of the mean values of the selected soil characteristics in the study wetland varied between the least and the most disturbed sites, and the results are presented in Table 1. All selected properties varied significantly according to one-way ANOVA (moisture content, pH, SOC, and TN) between LD and MD sites. Percent moisture was higher in the LD than in the MD ($F = 40.7$, $P < 0.001$). More so, pH was higher in MD than in LD (one-way ANOVA, $F = 52.8$, $P < 0.001$). Furthermore, SOC showed higher significant values in LD than in MD sites (One-way ANOVA, $F = 74.0$, $P < 0.001$). Likewise, STN was significantly higher in LD than in MD sites (one-way ANOVA; $F = 7.3$, $P < 0.01$). However, TP concentration in LD and MD did not vary significantly (one-way ANOVA, $F = 0.9$, $P > 0.05$).

Table 1: Characteristics of selected soil characteristics at King'wal wetland showing variations between the least disturbed (LD) and most disturbed (MD) sites during the study period (September 2021 to August 2022) (data depicts mean ± standard deviation of the mean, n = 144)

	Disturbance gradient	
Soil parameters	Least Disturbed	Most disturbed
Moisture content (%)	73.4 ± 16.1	61.8 ± 11.9***
pH	5.36 ± 0.42	5.97 ± 0.81***
Soil organic carbon (%)	3.66 ± 0.73	2.51 ± 1.3***
TP (mg P/Kg)	1005 ± 524	946 ± 462
TN (mg N/Kg)	51.7 ± 42.1	38.4 ± 33.2***

****statistically significant at p < 0.001*

Interaction between season and disturbance gradient on soil characteristics

A two-way ANOVA was conducted to assess whether seasonal changes and disturbance gradients interacted to influence soil characteristics. Figure 4 presents the interaction graphs of season and disturbance on soil characteristics. Results showed that season and disturbance significantly interacted with the soil moisture and pH in the wetland soil (Figure 4a & b). Two-way ANOVA depicted a significant interaction for soil moisture ($F = 5.8$, $P < 0.05$) and soil pH ($F = 3.8$, $P = 0.05$). Soil organic carbon and total nitrogen were influenced separately by season and disturbance (Figure 4c & e). Furthermore, there was no interaction between season and disturbance on soil total phosphorus (Figure 4d).

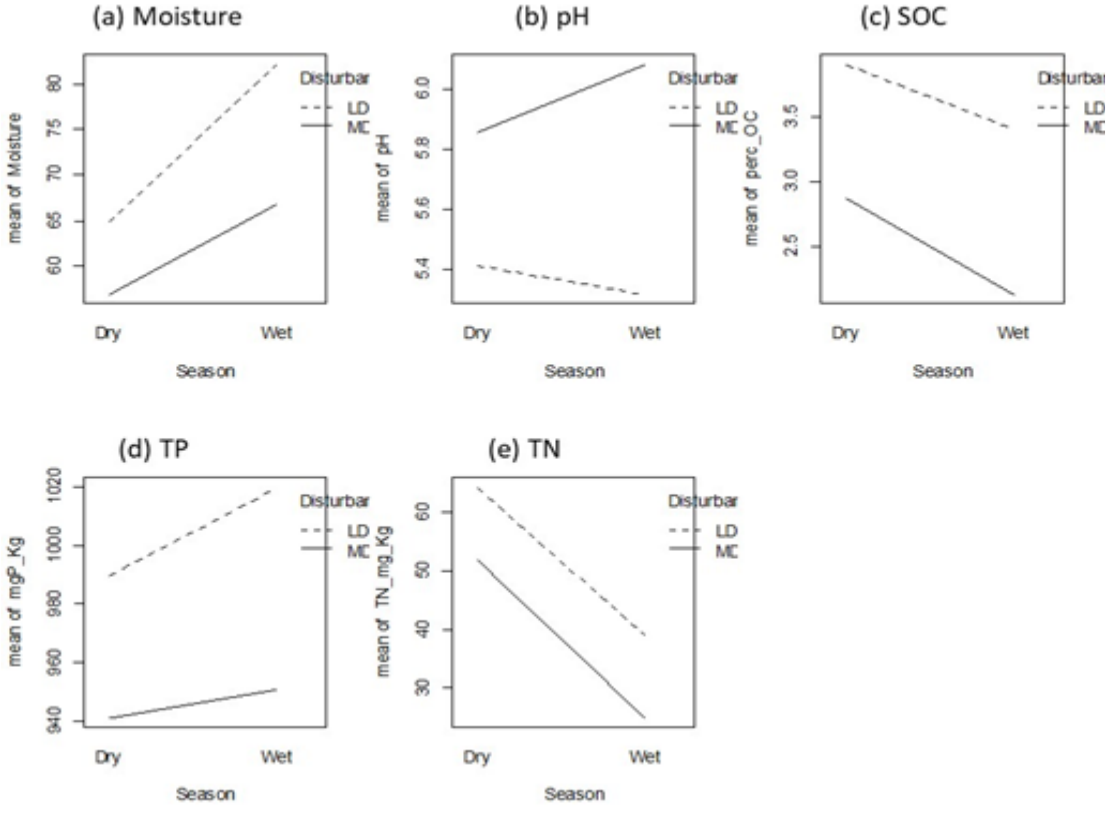

Figure 4: The interactions between seasons (dry and wet) and disturbance gradients (least disturbed and most disturbed) on soil characteristics (a) moisture, (b) pH, (c) Soil Organic Carbon (SOC), (d) Total Phosphorus (TP), and (e) Total Nitrogen (TN). Complete line depicts the most disturbed (MD), while dashed lines represent the least disturbed sites (LD)

Relationship between different soil characteristics

Table 2 presents the correlation matrix among soil characteristics in King'wal wetland. Soil pH had a significant negative correlation with soil moisture ($R = -0.19$, $P < 0.01$). Furthermore, soil moisture correlated negatively with STN, although the relationship wasn't significant ($R = -0.11$, $P > 0.05$). Although SOC and STP are positively correlated with moisture, the relationship was not statistically significant. On the other hand, soil pH was strongly and negatively correlated with SOC ($R = -0.53$, $P < 0.001$) and moderately with STN ($R = -0.33$, $P < 0.001$). However, a strong positive correlation was observed between SOC and STN ($R = 0.62$, $P < 0.001$) (Table 2).

Table 2: Correlation coefficient matrix showing the relationship among the selected topsoil (0 -10 cm) characteristics in King'wal wetland during the study period

	Moisture	pH	SOC	STP	STN
Moisture	1.00				
pH	-0.19**	1.00			
SOC	0.04	-0.53***	1.00		
STP	0.07	0.09	0.08	1.00	
STN	-0.11	-0.33***	0.62***	0.004	1.00

*SOC is soil organic carbon; STP soil total phosphorus; STN soil total nitrogen; Temp is air temperature while *statistically significant correlation at P < 0.05; **statistically significant correlation at P < 0.01; and ***statistically significant correlation at P < 0.001*

Relationship between climate variables and soil characteristics

Soil characteristics were influenced by climate variables (rainfall, water depth, and air temperature) in the wetland during the study period in different ways (Table 3). Water depth and rainfall showed a positive relationship with soil moisture, R = 0.21 and R = 0.26, respectively. However, temperature had a significant negative relationship with soil moisture (R = -0.41, P < 0.001) and water depth (R = -0.66, P < 0.001). Increased amounts of rainfall led to a significant reduction in percent SOC (R = -0.27, P < 0.001) and STN concentration (R = -0.25, P < 0.001) in King'wal wetland soil (Table 3). Furthermore, soil pH and STP increased significantly with an increase in rainfall amount, using Spearman's correlation matrix (R = 0.13, P = 0.05) and (R = 0.12, P < 0.05), respectively. The water depth in the wetland had a significant negative influence on soil organic carbon (SOC) (R = -0.28, P < 0.001) and soil total nitrogen (STN) (R = -0.23, P < 0.001) (Table 3). However, water depth did not influence the soil pH and STP significantly (P > 0.05) (Table 3).

Table 3: Correlation coefficient matrix showing the relationship between soil characteristics of topsoil (0 -10 cm) and climate variables (rainfall, water depth, and temperature) in King'wal wetland during the study period

	Moisture	pH	SOC	STP	STN	Rainfall	Water depth	Temp
Rainfall	0.26***	0.13*	-0.27***	0.12*	-0.25***	1.00		
Water depth	0.21**	0.07	-0.28***	-0.11	-0.23***	0.48***	1.00	
Temperature	-0.41***	-0.11	0.30***	0.32**	0.23***	-0.58***	-0.66***	1.00

*SOC is soil organic carbon; STP soil total phosphorus; STN soil total nitrogen; Temp is air temperature while *statistically significant correlation at P < 0.05; **statistically significant correlation at P < 0.01; and ***statistically significant correlation at P < 0.001*

Discussion

Wet and dry seasons influence soil characteristics in the King'wal wetland. Soil moisture fluctuates between these seasons, with the highest moisture levels during the wet season due to increased rainfall adding water to the soil. Soil moisture reflects the wetland soil, which is

typically saturated. However, during a prolonged dry season, there is a reduction in soil moisture, leading to dry soil that promotes dry land conditions. During the wet season, runoff from surrounding areas led to increased moisture in the soil, causing it to become saturated. Wetland soil exhibits high soil moisture, yet dry conditions that encourage evaporation and moisture loss can impact it. The amount of rainfall in the area can influence soil moisture—more rainfall generally results in higher soil saturation. This effect was observed in the wetland, which had high moisture levels during the study period, with a lowest mean of 60% in the dry season. Soil moisture is an important property that influences other soil characteristics in the wetland. Seasonality will likely affect the wetland if it extends beyond normal weather patterns. Changes in soil moisture are likely to modify the wetland's functions, especially regarding habitat for microorganisms, decomposition reduction or increase, and carbon sequestration, with wet soil enhancing it more than dry soil (Sprangler et al., 2021). Soil moisture is critical to wetland soil, and its alteration is the beginning of wetland degradation (Wang et al., 2023; Taylor et al., 2021). Changes in soil moisture will directly influence plant communities in the wetland (Peng et al., 2020). Hence, soil characteristics are important indicators for restoration activities in wetland ecosystems (Wan et al., 2024).

Soil pH, on the other hand, is also influenced by the season, with the wet season showing a slightly higher pH than the dry season. Although pH levels during the wet season were higher in this study, there was no significant difference between the wet and the dry seasons. This may have been influenced by the water flowing into the wetland during the dry season from created channels. Wetland soils are generally known to have a low pH below 6 due to humic acids formed under warm and wet conditions (Mitsch et al., 2013). Additionally, as plants die and decompose in the wetland, they contribute to lower soil pH, which leads to acidic conditions. An increased pH during the wet season may have resulted from the deposition of basic fertilizers from surrounding agricultural areas, which can make the soil more alkaline.

Soil organic carbon in wetlands is a critical characteristic that influences other soil properties (FAO, 2019; Ding et al., 2025). The presence of wetland plants helps add humus to the wetland soil as they grow, dry, and decompose, thereby increasing organic carbon in the soil. However, removal of the vegetation will decrease organic carbon in the wetland soil, which may buffer soil pH. (Shen et al., 2021).

Phosphorus and nitrogen varied between wet and dry seasons. Phosphorus is an important nutrient required by plants for their growth (Ebrahimi & Ojani, 2024). However, excess phosphorus in the wetland soil may lead to eutrophication of receiving wetlands, rivers, and lakes (Bertol et al., 2017). Total phosphorus in King'wal wetland, though slightly higher in the wet season, was not different from the dry season. Phosphorus in wetland topsoil was higher and did not vary with season in King'wal wetland. These results echo the findings in the temperate environments (Zhao et al., 2024; Lv et al., 2023). Total phosphorus in wetland soil is due to the accumulation of decomposed organic matter, which releases phosphorus to the soil surface; hence, high phosphorus in the wetland topsoil (Lu et al., 2022; Wiegman et al., 2024). At the same time, high phosphorus retained in the wetland soil makes the influence of season not significant (Lemanowicz, 2018). Most of the phosphorus may be deposited on the wetland from runoff after flash floods, which may lead to storage of phosphorus in the wetland soil when compared to the upland areas where erosion occurs (Ebrahimi & Ojani, 2024). Furthermore,

waterlogged soil creates anaerobic conditions that prevail in the wetland ecosystem, making phosphorus concentration in wetland topsoil high, inhibiting leaching (Nie et al., 2022; Trettin et al., 2020). Phosphorus is an important element in determining inland wetland ecosystem health as it supports plant growth. Likewise, nitrogen was higher in the dry season than in the wet season in King'wal wetland. This showed that dry conditions enhanced nitrogen cycling in the wetland while wet conditions inhibited microbial activities, hence, leading to reduction of nitrogen in the wetland topsoil (Wang et al., 2023; Winston & Richardson, 2017).

A disturbance gradient is created by human activities and aggravated by seasonal changes occurring in the locality. Assessing soil characteristics in least disturbed versus most disturbed sites showed variations in King'wal wetland. Wetland soil characteristics were affected by the disturbance gradient, with the least disturbed sites having better variables than the most disturbed sites. Disturbances from livestock grazing, farming, burning, and clearing reduced the percent of soil moisture, soil organic matter, soil total phosphorus, and soil total nitrogen in King'wal wetland. However, most disturbed sites had a higher and significant pH than the least disturbed sites. Least disturbed sites are characterized by high soil moisture with anaerobic conditions, which release humic acid, making the soil more acidic (Mitsch & Gosselink, 2015). The results are in harmony with the findings from other studies that showed that anthropogenic activities such as farming reduce soil organic carbon and soil nutrients, hence, accelerating rates of soil erosion and degradation (FAO, 2019; Mao et al., 2018; Robertson et al., 2019; Lishan & Regasa, 2022). For example, Winton & Richardson (2017) and Sprangler et al. (2021) suggested that disturbances from herbivores can indirectly influence nutrient cycling and alter biogeochemical processes in wetlands. Therefore, understanding changes in nutrient concentration in wetland soil is vital for identifying areas where restoration should be prioritized to support wetland vegetation and preserve soil properties.

The interaction between seasons and disturbance gradients varied across soil characteristics, with soil moisture and pH showing a significant interaction. Soil moisture and pH in inland wetlands are shaped by the interaction between seasonal changes (wet and dry) and disturbance events (burning, conversion of the wetland to cropland, and livestock grazing) that work in tandem. Seasonal variations (wet and dry seasons) lead to changes in soil moisture, and in turn, influence oxygen availability, microbial activity, and chemical reactions regulating the soil pH (Patil & Lamngenbi, 2018). However, soil organic carbon, total phosphorus, and total nitrogen did not exhibit a significant interaction between season and disturbance gradients. The season did not interact with the disturbance gradient for total phosphorus. Nevertheless, the disturbance gradient significantly affected total phosphorus, resulting in lower concentrations at the most disturbed sites.

Wetland soil characteristics influence each other to either reduce or increase their presence. Soil moisture and soil pH were critical soil characteristics that influenced other soil properties (organic carbon, nitrogen, and phosphorus) in King'wal wetland. Higher soil moisture negatively correlated with soil pH in King'wal wetland. These results agree with the findings from other studies (Njeru et al., 2017; Yang et al., 2024). On the other hand, soil pH negatively correlated with soil organic carbon and soil total nitrogen in King'wal wetland. These results are in harmony with the studies that showed that topsoil are rich in organic carbon, which decompose to produce humic acids,

lowering soil pH in the wetland (Zhou et al., 2019). Low soil pH enhances organic carbon and nitrogen accumulation in the soil as decomposition is controlled by acidic conditions. Most of the microbes that decompose organic matter are not active in the anaerobic environment; hence, more organic matter is deposited on the soil surface, adding more nutrients. However, as the pH was increased, there was less organic carbon in the soil since there was high microbial activity, making nutrients available for plants to take up (Hong et al., 2019). Soil organic carbon positively correlated with soil total nitrogen, while nitrogen and phosphorus concentration in wetland soil did not relate significantly. These relationships influenced the status of wetland soil quality, which maintains various ecological processes (Tura, 2020). Understanding factors determining soil characteristics in the context of climate change expected to be experienced globally, is important. This information helps managers to protect and manage wetland ecosystems by restoring soil health, which supports other goods and services that benefit society.

Wetland soils are sensitive to climate variability, which alters the wetland ecosystem over a long-term period (IPCC, 2023). Rainfall and water depth had a positive influence on the soil moisture in King'wal wetland. However, temperature had an inverse relationship with the rainfall, water depth and therefore, influenced other soil characteristics in King'wal wetland. Rainfall in King'wal wetland led to an increase in soil moisture, soil pH, and soil total phosphorus. However, it led to a decrease in soil organic carbon and soil total nitrogen in the wetland. This implies that most of the nutrients are released into the water and become available to wetland plants during the rainy season. This is because microbial processes that drive ecological functions such as mineralization, productivity, and decomposition are reduced in anaerobic conditions, leading to reduced nutrients available to plants. Other studies done in other regions have echoed the same results that the rainy season, enhances anaerobic conditions reducing the microbial activities; hence, reducing the release of these nutrients to the soil (Wang et al., 2023). These nutrients are carried away from the system to other areas, making the site soil lose nutrients, lowering soil nutrients in the soil during the wet season.

Temperature on the other hand, negatively influenced soil moisture and soil pH in the wetland. However, for soil pH the relationship with temperature was not significant. This could be due to the fact that there was a maintenance of soil moisture in the wetland, which led to a non-significant relationship in the seasonal changes as well as in the warmer conditions. Some of the acidity may have been due to the upland water that was brought into the wetland, which was coming from the surrounding agricultural farms. There was a positive relationship between temperature and the soil nutrients (soil organic carbon, total nitrogen, and phosphorus) in King'wal wetland. This could be due to accelerated microbial activities that enhanced decomposition of organic matter and release of nutrients into the soil. Management of inland wetlands is important in maintaining the positive interactions among the biotic and abiotic factors while minimizing the negative effects of climate variability through monitoring of soil characteristics in the field (Tura, 2020). The selected soil characteristics are influenced by the status of the ecosystem, which is affected by the seasonality and human-caused disturbances. Climate variables such as rainfall patterns and air temperature affect the status of the ecosystem by leading to an increase or a decrease in soil moisture. The novelty of this study was elaborating on the relationship between soil

characteristics and climate variables, including water depth, which is lacking in the King'wal region. This study can be compared with other studies done elsewhere to reduce problems affecting wetlands locally while contributing to global management of inland freshwater wetlands.

Implications of seasonal climate variability on soil characteristics

Soil characteristics studied are sensitive to seasonal climate variability (IPCC, 2023). Understanding how these characteristics interact with each other and with seasonal climate variability will help in identifying areas for conservation. These priority areas need to be protected to preserve processes that support soil health in the face of climate variability. Soil moisture and soil pH are the critical soil characteristics that influence other soil properties in King'wal wetland. This is due to their influence on other soil characteristics and are sensitive to climate variability, hence, drive change in the wetland structure and function (Wang et al., 2025). Critical soil moisture leads to a shift from wetland to dry land if the dry conditions continue to prevail, influencing the critical wetland functions such as biomass accumulation, decomposition and water purification, which are critical for human and environmental health (Fu et al., 2024).

Disturbances such as grazing or conversion of wetland to cropland is enhanced by seasonal effects on soil characteristics. This requires minimizing and managing disturbances through having schedules for grazing, fire management, and creation of buffer zones to reduce runoff and erosion. Furthermore, soil characteristics such as soil moisture and soil pH are indicators that are sensitive to climate variability, and they can be used as early warning indicators of wetland soil degradation; hence, monitoring can be incorporated in wetland conservation.

These results are important in understanding the effects of season and disturbance gradient to soil properties, and indirectly to the structure and function of the wetland. Understanding the changes that affect soil characteristics are important in wetland management and restoration plans. Due to global climate change, climate variability is expected to continue and will affect the wetland soil characteristics, and in turn, influence the ecosystem services supported by the wetland. The natural effects of seasonality coupled with the disturbance regime in the wetland will aggravate the problem by causing wetland soil degradation, affecting the vegetation, and in turn the organisms that rely on the ecosystem for their resources and habitat. Soil is important as it is the base for the growth of macrophytes, sequesters carbon, a habitat for crucial microbes that drive the ecological processes, and filters toxic substances (Were et al., 2020).

The accumulation of soil organic carbon can be influenced by climate variability via alterations in precipitation that impact water depth in wetland ecosystems. As the water depth in the wetland increases, soil organic carbon will decrease. These occurrences will affect the rates of accumulation and breakdown in the wetland, as indicated by Sapkopta et al. (2025). According to Were et al. (2020), wetlands can reduce the effects of climate change by sequestering substantial amounts of soil organic carbon. Understanding how changing seasonal climate factors affect soil resources in a disturbed environment is crucial for planning and managing this vital ecosystem, especially in inland wetlands.

The results of the interaction between human-induced disturbances and wetland soil characteristics will inform wetland managers to plan for adaptation to change. This is because climate variability is a global concern and requires an understanding of how various variables

interact to cause changes in the health status of the wetland ecosystem. Moreover, the information can be used in decision-making and for predicting future changes in these wetlands, as climate change is expected to continue. Furthermore, the interaction between seasonal climate variability and soil characteristics will help identify degraded areas for their restoration. It is important for wetland managers to plan to reduce human-induced disturbances to soil characteristics, as well as to engage local stakeholders.

Conclusion

Seasonal climatic variability significantly influenced soil moisture, soil organic carbon, and soil total nitrogen, but not soil pH and soil total phosphorus in King'wal wetland. Likewise, variation in soil characteristics was more pronounced in most disturbed than in least disturbed sites in King'wal wetland. Soil characteristics in King'wal wetland were influenced by season and anthropogenic disturbances. The interaction between season and disturbance gradients significantly influenced soil moisture and pH, but not SOC, STP, and STN. Seasonal climate variability influenced soil characteristics in different ways. Rainfall negatively correlated with SOC and STN in the wetland. However, rainfall positively correlated with moisture, pH, and STP. Temperature, on the other hand, correlated negatively with moisture and pH but positively with STP, STN, and SOC. This study has enhanced our understanding on the relationships between soil characteristics and seasonal climate variability. Seasonality interacts with anthropogenic disturbances to enhance changes in wetland soil characteristics. This information is useful in predicting the impact of current and future global changes on inland freshwater wetlands. Based on these results, the least disturbed areas had high nutrient concentrations and were influenced by seasonality. It is important to prioritize the protection of these areas for carbon sequestration and biogeochemical processes. Furthermore, human activities that affected the most disturbed sites included intensive livestock grazing, creation of channels, and agriculture, which influenced the variation in soil characteristics in the wetland. These activities can be regulated through zoning and the creation of a buffer zone to reduce negative impacts on soil health. This would restore organic carbon, which is a crucial parameter that affects other soil characteristics, especially in King'wal wetland. Local community members can help manage the wetland ecology and mitigate the harmful effects of disruptions. Furthermore, indigenous knowledge can be combined with science to maintain the ecosystem and adapt to unpredictability and a changing climate.

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