

Article

Hydrological Regime Determines Wetland Resilience to Agricultural Conversion: A Comparative Study of Peatland and Floodplain in China and Tanzania

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Abstract

Balancing wetland conservation with food security is a critical challenge for developing countries. This study compares land use change and its impacts on soil properties in two hydrologically distinct wetlands: the rain-fed Jinchuan Peatland in China and the flood-fed Kilombero Valley Floodplain (KVFP) in Tanzania. Using remote sensing data from 1990 to 2018 and soil physicochemical analysis, we found divergent reclamation trajectories. Wetland conversion has slowed in China but accelerated in Tanzania's KVFP due to population pressure. Our results reveal a fundamental mechanism: rain-fed wetlands, lacking external nutrient replenishment, experience significantly greater soil degradation after conversion compared to flood-fed wetlands, which benefit from continued alluvial sediment inputs. Both sites showed post-conversion declines in soil moisture, total organic carbon (TOC), and total nitrogen (TN), alongside increased pH and bulk density. However, soil fertility loss was markedly more severe in Jinchuan than in KVFP. This disparity is attributed to the inability of rain-fed systems to replenish nutrients externally, whereas flood-fed KVFP benefits from continued alluvial sediment inputs. Our findings elucidate a key mechanism: flood-fed wetlands possess a natural resilience to agricultural disturbance through hydrological replenishment, making them potentially more suitable for sustainable utilization in food-insecure nations. Consequently, we propose that wetland management policies must be customized based on water source type and national development context, advocating for the targeted, science-based utilization of flood-fed wetlands as a strategic approach to reconcile food production with ecosystem preservation in regions like Tanzania.

Keywords: rain-fed wetlands; flood-fed wetlands; wetland; land use change; soil properties; food security; sustainable management



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1. Introduction

Wetlands store carbon as they offer the best natural environment to isolate and store carbon for a long time [1]. Despite their importance, wetland ecosystems globally have been degraded, with losses between 64% and 71% in the 20th century, and this continues in the 21st century, with large and rapid declines for inland swamps and floodplains compared to coastal wetlands [2]. The main cause of wetland loss is the reclamation of

wetlands into farmland [3]. Wetland conversion to agricultural land may affect wetland soil quality [4]. Soil quality is the functional capacity of the soil, measured by physical and chemical characteristics [5]. When land use types change, soil physical properties are good indicators of soil structural stability and quality [6]. Soil chemical properties such as soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) content have been recognized as indicators of soil quality that alter due to land cover change, tillage practices, and harvest [7]. However, the effects of land use change on wetland soils often go unnoticed, such that land managers rarely contemplate initiating restoration measures [8].

Recent impacts of agricultural land use change on wetland soil quality, understanding of soil properties, and processes have drawn the attention of most researchers [9]. Although several studies have described wetland use changes and intensification impacts on soil properties [10–12], little is known about the differential effects of agricultural conversion across wetland types with contrasting hydrological regimes. In particular, the concept of wetland resilience—defined here as the capacity of a wetland to maintain its soil functions following agricultural conversion—has rarely been examined. In disturbance ecology, resilience can be understood in multiple ways. Engineering resilience (or resistance) refers to the ability of a system to retain its core properties under a persistent disturbance, measured by the degree of deviation from an undisturbed reference state. Ecological resilience, in contrast, emphasizes recovery dynamics, thresholds, and regime shifts over time. This study adopts the engineering resilience framework: we compare converted farmland soils to adjacent natural wetland soils (the reference state) and use the magnitude of change in key soil properties—soil organic carbon (SOC), total nitrogen (TN), bulk density (BD), and pH—as inverse indicators of engineering resilience. A smaller post-conversion departure indicates higher capacity to maintain soil functions under agricultural use. From this resilience perspective, wetlands that receive continuous external nutrient inputs through hydrological pathways may be better able to resist degradation, whereas hydrologically isolated wetlands may be more susceptible. Understanding how hydrological regime mediates the capacity of wetland soils to resist agricultural degradation is therefore critical for developing sustainable wetland management strategies, especially in regions where food production pressures inevitably lead to wetland use.

China and Tanzania are typical agricultural countries in Asia and Africa, respectively, but they differ substantially in climate, soil background, and agricultural development history. China has a long history of farming with relatively advanced agricultural infrastructure, whereas Tanzania only began to develop agriculture on a large scale in modern times under largely rain-fed and flood-recession conditions. The two countries thus represent different stages of agricultural development and contrasting natural settings. Despite these confounding factors, both countries have experienced wetland reclamation for farmland, making them suitable for a comparative analysis focused specifically on the role of hydrological regime. Within each study site, we compared natural wetland soils with soils from adjacent farmland that had been converted from the same wetland. Because the natural and converted plots are located in the same climate zone and on the same soil type, any differences between them can be attributed mainly to agricultural conversion itself, rather than to differences in climate or soil background. We then compared the conversion effects observed at the two sites. Since one site is rain-fed and the other is flood-fed, this comparison allows us to assess whether the regular input of water and nutrients from river flooding can help buffer wetland soils against degradation caused by farming. China has largely ceased wetland reclamation after achieving food security, whereas Tanzania continues to convert wetlands—particularly flood-fed systems—to address food shortages [13]. These contrasting national contexts, combined with the distinct hydrological regimes of

the two selected wetlands, provide a unique opportunity to examine how hydrological connectivity influences wetland resilience to agricultural disturbance.

This study explores the effects of agricultural land use change on selected soil physicochemical properties in the rain-fed Jinchuan Peatland (China) and the flood-fed Kilombero Valley Floodplain (Tanzania). We address three questions: (1) How did agricultural land use change from 1990 to 2018 in the two wetlands? (2) What are the significant differences in soil physicochemical properties among land use types and soil depths? (3) How do the impacts of agricultural conversion differ between rain-fed and flood-fed wetlands, and what role does hydrological regime play in determining wetland resilience? The findings aim to contribute scientific knowledge on how different wetland soils respond to agricultural conversion and to provide resilience-based insights for wetland management policies that balance conservation with food production.

2. Materials and Methods

2.1. Study Sites Description

2.1.1. Jinchuan Peatland, China

Jinchuan Peatland lies between latitude $42^{\circ}20'56''$ N and longitude $126^{\circ}22'51''$ E, located in the core area of Longwan National Nature Reserve at an elevation of 613–617 m above mean sea level (Figure 1). The peatland is part of the Changbai Mountains, on the western edge of the Longgang Mountain area in Northeast China [14]. It belongs to a humid monsoon climate in the northern temperate zone, with an average annual temperature of 4.1°C , an average annual maximum temperature of 5.1°C , and a minimum temperature of 3.1°C [15]. Annual precipitation averages 704.2 mm/year, 61% of which occurs in summer, and evaporation is 1276 mm in summer [15].

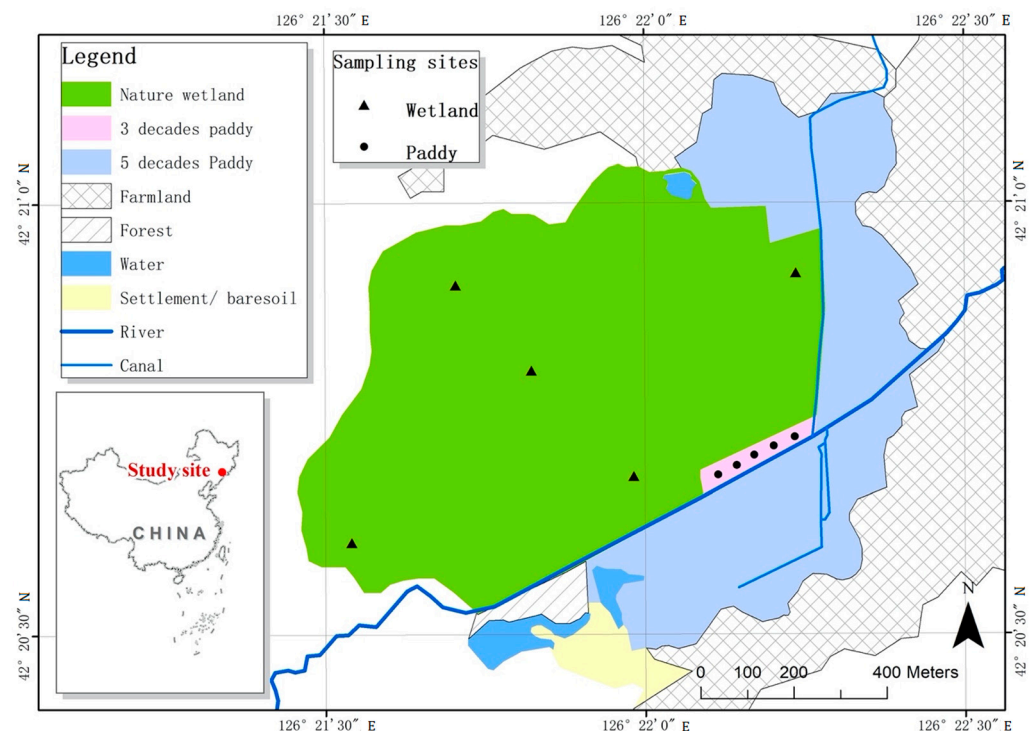


Figure 1. Jinchuan Peatland, Northeast China location: land use types and sampling points.

Geologically, Jinchuan Peatland evolved from a crater lake and originally received water from both precipitation and a small river flowing along its southern margin. Before agricultural development in the 1960s, this river passed through the lower southern edge of the wetland, maintaining a natural hydrological connection. Historically, the wetland

received water from precipitation, northwestern hillslope runoff, and seasonal flooding from a river along its southern margin. During agricultural reclamation in the 1970s, this river was straightened, diverted, and embanked, completely severing surface water and sediment inputs from the river. Runoff from the northwestern hillslopes still contributes a limited amount of water. Importantly, the peat layer is underlain by an impermeable gley horizon clay, which precludes any groundwater discharge into the wetland. Consequently, precipitation has become the dominant water source, and the wetland now functions as a rain-fed system.

Soils are typical peat with organic matter (OM) content greater than 40%. According to the WRB classification, the soil of Jinchuan peatland is classified as Fibric Histosol (organic soil with >40% organic matter, dominated by poorly decomposed fibric material). In USDA Soil Taxonomy, it corresponds to Saprist (great group) under Histosols. During the 1970s to 1990s, wetland areas were reclaimed for farming, mainly rice. The eastern and southern wetlands were reclaimed into paddy fields around 1970 (light blue patches in Figure 1). A small part of the southeast was reclaimed into paddy fields around 1990 (pink patch in Figure 1). The farming system is mainly irrigation agriculture, whereby artificial channels damming water are constructed by local farmers for rice cultivation.

2.1.2. Kilombero Valley Floodplain (KVFP), Tanzania

The study was conducted in the Mofu and Mbingu Wards in the floodplain of the Kilombero Valley between latitude 10°00′–08°40′ S and longitude 37°10′–35°10′ E, which belongs to Kilombero, Ulanga, and Morogoro, Malindi Region, Southeastern Tanzania (Figure 2). KVFP is the largest inland freshwater wetland in East Africa with low elevation [16]. This valley is divided by the Kilombero River, which begins on the southwest side where the Mpanga, Mnyera, and Ruhuji rivers enter the valley [17]. The valley has two peaks of rainfall with an average annual rainfall of between 1200 and 1400 mm; short rains are from December to February and persistent rains from March to May. The annual average temperature is 23 to 25 °C [18].

The dominant soils of KVFP are Eutric Fluvisols (WRB), characterized by stratified alluvial deposits with high base saturation. In USDA Soil Taxonomy, they are classified as Fluvaquents (great group) under Entisols [19]. KVFP is characterized by permanent swamps closely restricted to the vicinity of channels and some lagoons and was considered for this study as one of the largest inland tropical freshwater wetlands in East Africa. KVFP provides important ecosystem services that support human welfare and critical habitat for diverse plant and animal species. However, due to population growth, national policies, and biophysical factors, land use change in KVFP has led to deforestation, agriculture intensification, and expansion [20], resulting in soil degradation. Since the mid-19th century, the cultivation system of people living in the Kilombero Valley had been predominantly rain-fed subsistence farming, especially rice paddy [21]. The farming system depends on runoff from tributaries inundated by the Kilombero River, so suitable land is limited to the narrow riverside.

2.2. Method for Land Use Change Analysis

Quantitative land use change analysis using remote sensing was conducted only for the Kilombero Valley Floodplain (KVFP), where large-scale wetland conversion occurred during the study period. For Jinchuan Peatland, post-1990 reclamation was limited in extent, and land use change was assessed through field surveys, historical records, and landowner interviews. The wetland–farmland boundary is sharply defined by the peatland margin, and the presence of residual peat beneath the cultivated layer confirmed the

wetland origin of the converted farmland. Given the minimal area change, a quantitative remote-sensing analysis was deemed unnecessary for this site.

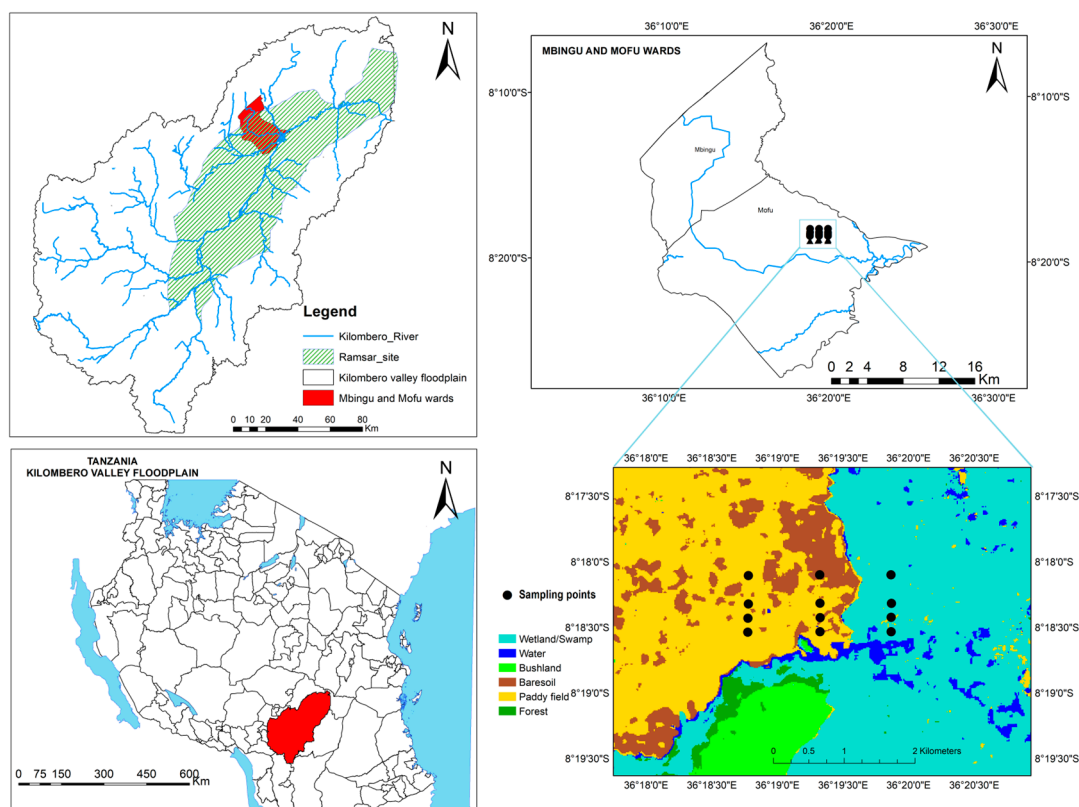


Figure 2. KVFP, Southeastern Tanzania location: land use types and sampling points.

Multi-spectral Landsat imageries acquired from two separate dates, 1990 (Landsat-5 Thematic Mapper (TM), NASA, Washington, DC, USA) and 2018 (Operational Land Imager (OLI), NASA, Washington, DC, USA) (Table 1), were employed to assess land use change of KVFP. These satellite images were downloaded for free from the archives of the USGS (Reston, VA, USA) and Earth Explorer (Sioux Falls, SD, USA), with a spatial resolution of 30 m. Before interpretation, atmospheric correction and geometric correction were performed. Image processing and data processing were carried out using ArcGIS 10.2 software (Esri, Redlands, CA, USA), whereby a maximum likelihood algorithm was used to perform supervised classification. Land use/cover was classified into six types: agriculture, water, wetland, settlement/bare soil, bushland, and forest (Table 2). This study used a classification scheme that closely followed the approach described in the IPCC's Good Practice Guidance for LUC [22], which was adopted by the Tanzania Land Use Planning Commission.

Table 1. Description of imagery data used in KVFP.

Satellite	Spectral Range (μm)	Band	Resolution	Image Date	Path/Row
Landsat (TM) 5	0.45–2.35	7	30 × 30 m	20 June 1990	166/65, 168/66
Landsat (OLI) 8	0.43–1.39	9	30 × 30 m	20 July 2018	166/65, 168/66

Source: <http://glovis.usgs.gov/> (accessed on 13 March 2019).

Table 2. Description land use classification system and type.

Land Use/Cover Types	National Land Cover Description
Forest	The area has a tree crown cover of 10% and a potential to reach a minimum height of 3 m.
Bushland	Areas are being predominantly comprised of plants that are multi-stemmed from a single root base.
Agriculture	The area is actively cultivated with agriculture crops.
Settlement/bare soil	Land includes a settlement and/or bare land, with rock outcrop.
Water	The area includes inland water, such as rivers and lakes, and the Indian Ocean.
Wetland	This is an area made up of swamps or marshes, and it is saturated land.

Source: good practice guidance for land use (IPCC, 2003) [22].

To assist supervised classification, an accuracy assessment was performed using a ground-truthing survey. A total of 149 ground control points were collected from all land use types using a Global Positioning System device, from which classification training sites and image space signatures were computed. Accuracy assessment results indicated overall accuracy, and Kappa coefficient were 94.44% and 0.92 in 1990 and 85.9% and 0.80 in 2018. The overall accuracy of the overall classification results was 89.8%, and the Kappa coefficient was 0.86. These results satisfied accuracy test requirements. Thus, the data were suitable for further analysis of land use change. The percentage change of land use types between 1990 and 2018 was calculated using Equation (1):

$$\Delta A\% = \frac{A_{t2} - A_{t1}}{A_{tt}} \times 100 \quad (1)$$

where $\Delta A\%$ indicates the percentage of land use change in the study area, A_{t1} and A_{t2} are the area of land at the beginning and end in the study area respectively, and A_{tt} is total area of land in the study area.

2.3. Soil Sampling Design and Collection

2.3.1. Jinchuan Peatland

For the Jinchuan Peatland, the natural wetland boundary was readily identifiable in the field due to a sharp, visually distinct margin between the peatland and the surrounding arid uplands. This clear demarcation allowed easy separation of wetland from dryland. Furthermore, the presence of residual peat layers beneath the rice paddy fields provided direct evidence that these agricultural plots were historically part of the peatland and had been converted from natural wetland. In Jinchuan Peatland, soil samples were collected in August 2018 to compare physical and chemical properties of samples that had changed from wetland to farmland. Wetland soil samples were used as reference points. Wetland soil sampling adopted the intersection method, where the first sampling point is the center of the wetland as the intersection, and the other four midpoints are the four edges (Figure 1). Soil samples from the reclaimed farmland (former wetland converted to paddy fields, cultivated continuously for 30 years after conversion) were collected using the transect line method. Five points along the long axis of agricultural land, equidistant from beginning to end, were selected as sample points (Figure 1). At each sample point, three replicate samples were collected from the topsoil layer (0–20 cm) and subsoil layer (20–40 cm), making a total of 60 samples.

2.3.2. KVFP

Soil samples for the Kilombero Valley site were collected in August 2018. Site selection was based on already produced LUC maps. Samples were collected from wetland and adjacent converted paddy fields that had been continuously planted for 10 years after conversion from wetland. Natural wetland reference areas were identified from the 1990 land use classification map (Figure 3a), which was validated by 149 ground control points. Wetland spectral signatures were clearly separable from other land cover types, yielding high classification accuracies for both periods. Sampling transects were placed entirely within the classified wetland polygon to ensure reference soils represented undisturbed wetland conditions. In the KVFP study area, soil sampling points were established along 4 parallel transects, each 1 km in length. Each transect originated within the wetland interior and extended linearly into the adjacent agricultural land, ensuring that both land use types (wetland and cropland) were covered along the same transect for direct comparison. Along each transect, 1 sampling point was placed in the wetland section and 2 sampling points in the agricultural section, resulting in a total of 12 points (4 wetland points and 8 paddy field points) across the 4 transects. At each sample point, 3 replicate samples were collected from topsoil (0–20 cm) and subsoil (20–40 cm). Soil design differs due to differences in area coverage; the KVFP area is larger than Jinchuan Peatland. Undisturbed soil samples were collected using a 100 cm³ stainless steel core sampler (Eijkelpamp, Giesbeek, The Netherlands) from topsoil and subsoil. Core samples were taken out, freshly weighed, and dried in a laboratory oven (Binder, Tuttlingen, Germany) at 105 °C to determine bulk density (BD) and soil moisture. Other soil samples were collected in plastic zipper bags (Whirl-Pak, Nasco, Fort Atkinson, WI, USA) and transported to soil laboratories for fertility analysis.

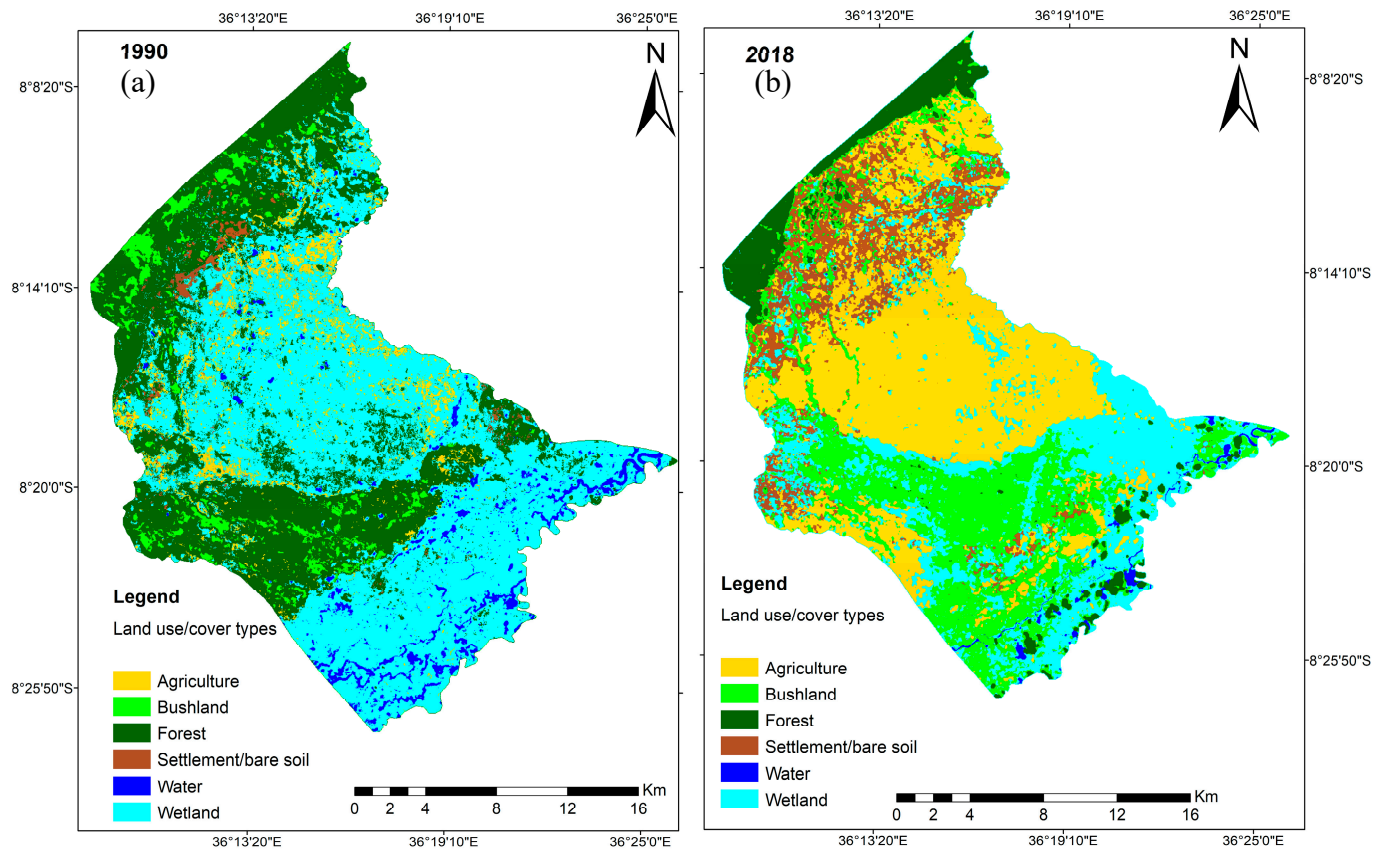


Figure 3. Land use maps of the study site in the KVFP: (a) LUC map in 1990 and (b) LUC map in 2018.

2.4. Soil Data Analysis

Soil samples from Jinchuan Peatland and KVFP were analyzed at the soil laboratory of the National Key Laboratory of Wetland Ecology and Vegetation Restoration, Northeast Normal University, China, and the soil laboratory of Sokoin Agricultural University (SUA), Tanzania, respectively. Prior to laboratory analysis, soil samples were air-dried and sieved with a 2 mm stainless steel screen (Retsch, Haan, Germany). Soil characteristics considered were SOC, TN, pH, BD, and TP. TOC was determined by wet sulfochromic oxidation followed by FeSO_4 ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, $\geq 99\%$, Sigma-Aldrich, St. Louis, MO, USA) [23]. TN was determined by the Kjeldahl process using a Kjeltac 8400 analyzer (Foss, Hillerød, Denmark) and TP by ammonium molybdate spectrophotometry (UV-2600 spectrophotometer, Shimadzu, Kyoto, Japan) [24]. Soil pH was determined potentiometrically with an electronic pH meter (FE28, Mettler Toledo, Columbus, OH, USA) in a 1:2.5 soil-to-water suspension [25]. BD was determined using the core method, with samples oven-dried at 105°C to constant weight in a forced-air drying oven (Binder, Tuttlingen, Germany) [26]. To ensure cross-site comparability of analytical results, both laboratories applied standard methods for all soil parameters and implemented consistent quality control procedures, including reagent blanks, triplicate determinations, and calibration with certified reference materials. All samples were uniformly air-dried and sieved (<2 mm) before analysis. Certified reference soil materials (GBW07401, National Research Center for Certified Reference Materials, Beijing, China; ISE 859, Institute for Reference Materials and Measurements, Geel, Belgium) were used; duplicate samples (10% of total) were exchanged and analyzed in both labs with deviation $<5\%$. Soil C/N and C/P ratios were calculated by dividing TOC by TN and TP concentrations, respectively.

To test for significant differences in soil physicochemical properties among different land uses and soil depths, an independent samples *t*-test was employed ($p < 0.05$). For each study site and soil depth, the effect of agricultural conversion on each soil physicochemical property was quantified as the change in the mean value: $\Delta = \text{farmland mean} - \text{wetland mean}$ (negative values indicate a decline after conversion). To test the core hypothesis—whether the magnitude of soil degradation differs between the rain-fed and flood-fed wetland systems—the derived Δ values were compared between Jinchuan Peatland and KVFP using independent samples *t*-tests. This comparison was performed separately for each soil depth (0–20 cm and 20–40 cm) and each soil property. No between-depth comparisons were made.

A methodological novelty of this study is the paired-site cross-national comparison of two hydrologically distinct wetlands (rain-fed vs. flood-fed) using a within-site paired sampling design (natural wetland vs. adjacent converted farmland) combined with cross-site comparison of conversion effects. This design controls for local soil and climate differences while allowing examination of hydrological regime effects. However, several limitations should be acknowledged: (1) only two sites are included, limiting generalizability. (2) The sites differ in multiple confounding factors (soil type, climate, cultivation duration) beyond hydrology; (3) the cross-sectional design captures only one time point; and (4) laboratory analyses were performed in different countries, although cross-calibration was implemented. All statistical analyses, including independent samples *t*-tests, were performed using SPSS Statistics version 26 (IBM, Armonk, NY, USA).

3. Results

3.1. Land Use Change in the Study Sites

Based on field surveys, historical records, and landowner interviews, only a minor fraction of the Jinchuan Peatland (estimated at less than 5% of the wetland area) was converted to farmland after 1990, with the majority of reclamation having occurred during

the 1970s. The farmland is exclusively under rice cultivation, irrigated via artificial channels. In contrast, the natural wetland area remained largely stable, protected within the Longwan National Nature Reserve. The farming method in Jinchuan Peatland involves construction of artificial river channels to drain the wetland for agricultural land, mainly for rice farming. The artificial channel bed is far below the surface, so the original flood valley wetlands cannot receive natural water supply. Paddy fields are irrigated by artificial channels damming water; river water cannot enter directly into paddy fields during floods, so nutrients carried by river water during this period are rarely deposited in paddy fields. The selected paddy field, mainly formed by wetland drainage, has been continuously under rice cultivation for about 30 years.

In regards to KVFP, spatial and temporal trends of land use change were analyzed using a maximum likelihood algorithm-supervised classification method over the past 28 years (Figure 3). The wetland has a higher proportion of area coverage of about 51%, the second is the forest of about 35%, while agricultural land had a low proportion of 6% of the total area in 1990 (Table 3). In 2018, the area of wetland decreased and became almost equal to bushland. The comparison of the land use for each category between 1990 and 2018 showed that wetland had declined by 145 km² (28%) and forest by 140 km² (28%). However, agriculture land had increased by 155 km² (31%), bushland by 96 km² (19%), and settlement/bare soil by 47 km² (9%) in 2018. Over the 28 years from 1990 to 2018, wetland and forest areas have decreased and converted to other land use, mainly to agriculture. Agriculture areas have shown an increasing trend by 31% (Table 3 and Figure 3).

Table 3. Land use change at Mofu and Mbingu wards in the KVFP during 1990–2018.

Land Use/Cover Types	Land Use Change					
	1990		2018		1990–2018	
	Area (km ²)	Ratio (%)	Area (km ²)	Ratio (%)	Area (km ²)	Ratio (%)
Wetland	260	51	116	23	−145	−28
Water bodies	18	3	4	1	−14	−3
Agriculture	28	6	184	36	155	31
Settlement/Bare soil	6	1	53	10	47	9
Bushland	21	4	117	23	96	19
Forest	175	35	35	7	−140	−28
Totals	509	100	509	100	-	-

3.2. Soil Physicochemical Properties in the Study Sites

The selected soil physicochemical properties of the topsoil (0–20 cm) and subsoil (20–40 cm) for the Jinchuan peatland and KVFP are presented (Figure 4). In both study sites, the soil pH was generally acidic for both the wetland points and the agricultural land points ranging from 5.17 to 6.77. In Jinchuan, mean BD increased from 120 kg m^{−3} in wetland to 561 kg m^{−3} in agricultural land (0–20 cm) and in KVFP, from 850 kg m^{−3} to 1050 kg m^{−3} (0–20 cm). Soil moisture declined following wetland conversion at both sites, although the decline was not statistically significant in Jinchuan Peatland (Figure 4). In Jinchuan, mean soil moisture was approximately 51% (0–20 cm) and 61% (20–40 cm) in the wetland, compared to approximately 49% and 57% in the farmland. In KVFP, the decline was more pronounced and statistically significant: from approximately 58% to 16% in the 0–20 cm layer and from approximately 61% to 16% in the 20–40 cm layer (Figure 5). In Jinchuan peatland, 0–20 cm concentrations of total organic carbon (TOC) and TN decreased from 484.01 to 212.59 g/kg and 15.70 to 7.17 g/kg, respectively, whereas in KVFP TOC decreased from 66.17 to 18.14 g/kg, and its TN decreased from 3.65 to 1.23 g/kg (Figures 4 and 5). It should be noted that the two study sites differ not only in hydrological regime but also in climate, parent material, and soil type. Therefore, direct comparisons of

absolute soil property values between sites are not meaningful. The comparison of interest is the relative magnitude of change following agricultural conversion within each site.

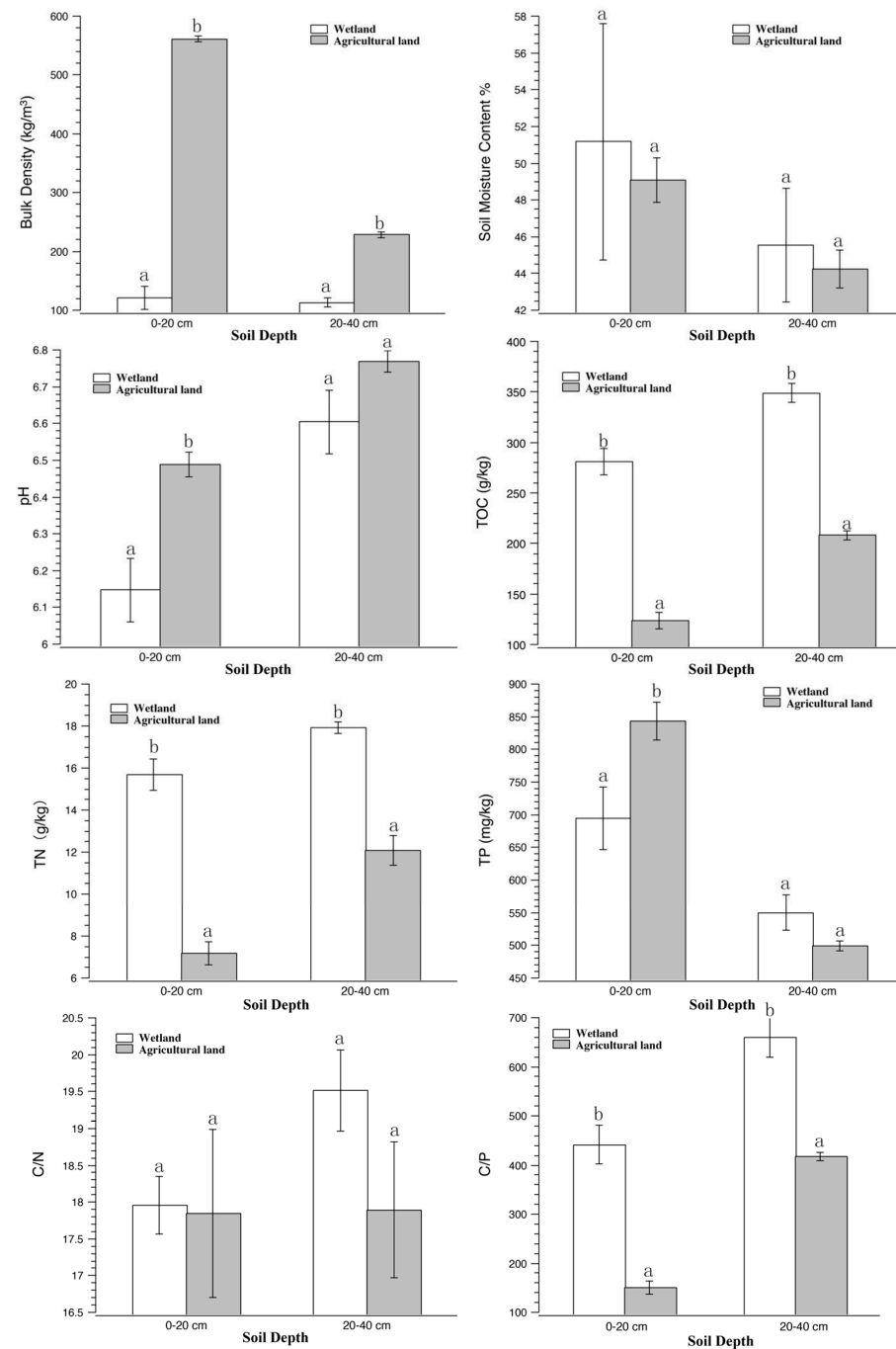


Figure 4. Selected soil physicochemical properties in surface (0–20 cm) and sub-surface (20–40 cm) soil layers as influenced by agricultural land use change in Jinchuan wetland. NB: Bars represent standard error of the mean (*n* = 15 for wetland and agricultural land respectively). Different letters indicate significant differences by independent samples *t*-test at *p* < 0.05.

3.3. Soil Chemical Properties in Jinchuan Peatland

In regards to the chemical properties of the soil at depths of 0–20 cm, the soil analysis results of topsoil samples from wetland and agricultural land points in Jinchuan peatland were characterized for the major soil quality indicators to see the trend of the selected soil physicochemical properties as a function of agricultural land use change. The results of an independent samples *t*-test at *p* < 0.05 revealed that there was a statistically significant

difference among the mainland use on soil pH, BD, TOC, TN, TP, and C/P ratio in the Jinchuan peatland. The TOC, TN, and C/P ratio of the agricultural land were observed to decrease significantly when wetland changed to agricultural land, whereas soil pH, BD, and TP of agricultural land significantly increased. In contrast, soil moisture and C/N ratio were not significantly affected by wetland conversion to agricultural land (Figure 4).

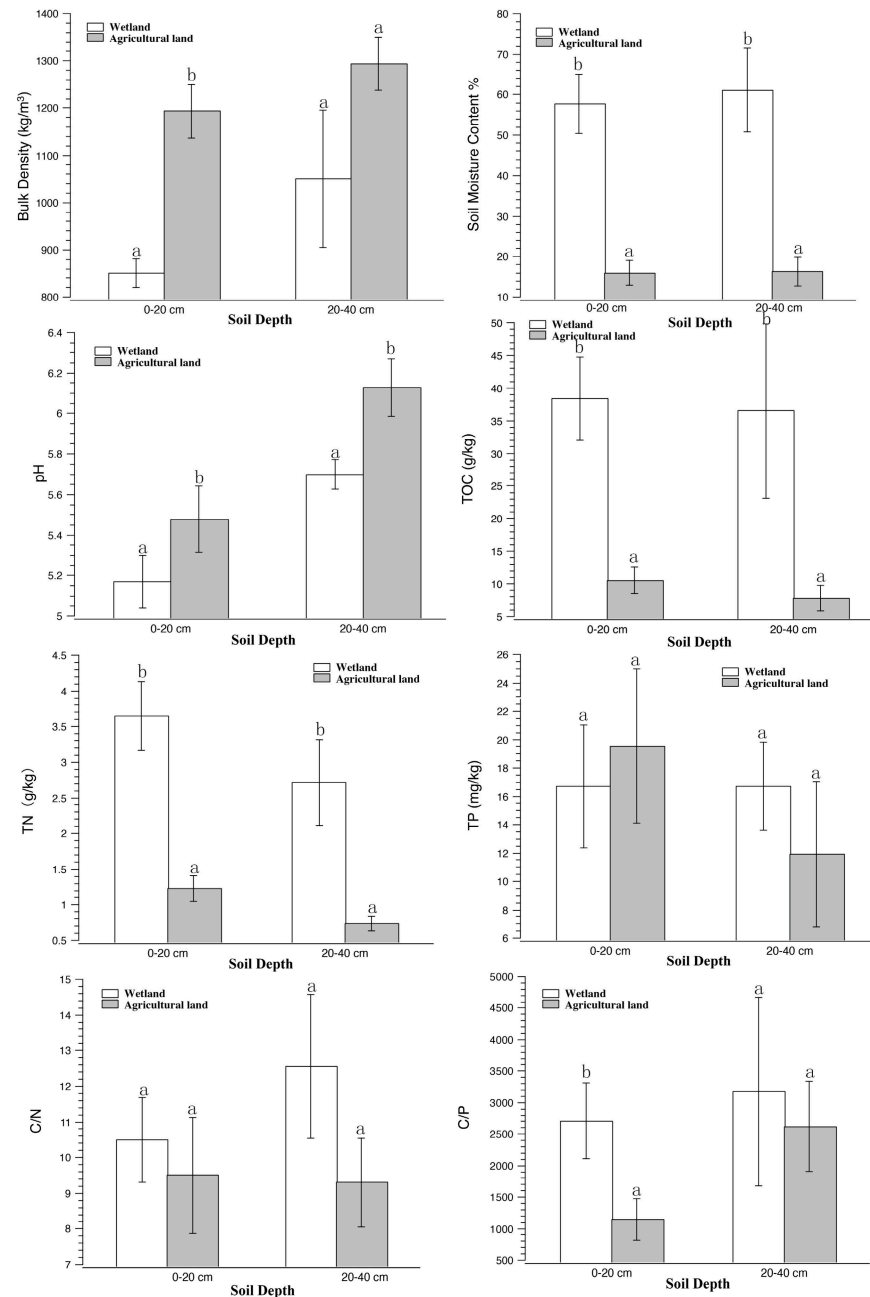


Figure 5. Selected soil physicochemical properties in surface (0–20 cm) and sub-surface (20–40 cm) soil layers as influenced by agricultural land use change in KVFP. Bars represent standard error of the mean ($n = 12$ for wetland and $n = 24$ for agricultural land). Different letters indicate significant differences by independent samples *t*-test at $p < 0.05$.

In regards to the soil depth of 20–40 cm, the soil analysis results of sub-surface soil samples from wetland and agricultural land points in Jinchuan peatland were characterized for the major soil quality indicators. The independent samples *t*-test result at $p < 0.05$ indicates that there was a significant difference between wetland and agricultural land for BD, TOC, TN, and C/P ratio in the 20–40 cm layer. TOC, TN, and C/P were observed to

decrease dramatically in the 20–40 cm layer when wetland changed to agricultural land. The BD seems to significantly increase, which was higher in agricultural land than the wetland. In contrast, the moisture, soil pH, TP, and C/N ratio of soil were not significantly affected with the wetland conversion to agriculture land use (Figure 4).

3.4. Soil Chemical Properties in the KVFP

In regards to the soil depth of 0–20 cm, the soil sample analysis of the topsoil (0–20 cm) from wetland and agricultural land points in KVFP were characterized for the major soil quality indicators to see the trend of the selected soil physicochemical properties' responses as a function of agricultural land use change. There was a significant difference (t -test at $p < 0.05$) on soil pH, BD, soil moisture, TOC, TN, and C/P ratio among the main land use in the 0–20 cm layer. The TOC, TN, soil moisture, and C/P ratio of the agricultural land were observed to decrease when wetland changed to agricultural land, whereas soil pH and BD of agricultural land significantly increased. In contrast, TP and C/N ratio were not significantly affected by wetland conversion to agriculture land use (Figure 5).

In regards to the soil depth of 20–40 cm, the soil sample analysis results of sub-surface soil samples from wetland and agricultural land points in KVFP were characterized for the major soil quality indicators to see the trend in the selected soil physicochemical properties' response as a function of agricultural land use change. The independent samples t -test at $p < 0.05$ result indicates that there was a significant difference among main land use type on soil moisture, pH, TOC, and TN in the 20–40 cm layer. Also, the TOC, TN, and soil moisture were observed to significantly decrease in the 20–40 cm layer when wetland changed to agricultural land, while soil pH appears to be significantly higher in the agricultural land than the wetland. In contrast, soil moisture, BD, TP, C/P, and C/N ratio were not significantly affected by the wetland conversion to agriculture land use (Figure 5).

3.5. Comparison Effects of Land Use Change on Soil Properties in the Study Sites

In regards to the soil depth of 0–20 cm, the results of the independent samples t -test at $p < 0.05$ on soil physicochemical properties, with the wetland type as an independent variable, revealed that there is a significant difference between TP, soil pH, TOC, TN and C/P ratio between Jinchuan peatland and KVFP when wetland changed to agricultural land. On the test, the increase in TP ($t = 4.399$, $p = 0.000$) was significantly greater for Jinchuan peatland than KVFP after wetland change to the agricultural land (Table 4). Soil pH of the KVFP increased significantly by 0.19, compared to the Jinchuan peatland, after the wetland changed to agricultural land. TOC ($t = -13.817$, $p = 0.000$) and TN ($t = -9.719$, $p = 0.000$) declined significantly in Jinchuan peatland than KVFP ($p < 0.05$). In KVFP, C/P has shown to significantly decrease ($t = 4.292$, $p = 0$) ($p < 0.05$) compared to Jinchuan peatland. Besides, there are no significant differences between Jinchuan peatland and KVFP in BD, C/N ratio and soil moisture after wetland changed to agricultural land ($p < 0.05$) (Table 4). In regards to the soil depth at 20–40 cm, the result of the independent samples t -test at $p < 0.05$ on the soil physicochemical properties, with wetland type as an independent variable, is provided in Table 4.

There is significant difference between the C/P ratio, TOC, TN, and TP between Jinchuan peatland and KVFP when wetland changed to agricultural land. C/P of KVFP increased by 1473.9, while Jinchuan peatland decreased by 242.3 ($p < 0.05$). The decrease in the content of TOC ($t = -27.278$, $p = 0.004$), TN ($t = -6.712$, $p = 0$), and TP ($t = -4.522$, $p = 0$) was observed to be significantly higher for the Jinchuan peatland than KVFP ($p < 0.05$) (Table 4). There are no significant differences ($p < 0.05$) between the Jinchuan peatland and KVFP for the soil pH, BD, C/N ratio, and soil moisture after agricultural land use change (Table 4).

Table 4. Comparison of the magnitude of agricultural-conversion-induced changes (Δ) in soil physicochemical properties between Jinchuan Peatland and KVFP.

Depth	Soil Properties	<i>t</i> Value	df	Sig.	Mean Difference	Std. Error Difference
0–20 cm depth	Soil pH	−2.481	25	0.020	−0.188	0.076
	BD (kg/m ³)	1.919	25	0.067	97.198	50.661
	TOC (g/kg)	−13.817	25	0.000	−129.583	9.378
	TN (g/kg)	−9.719	25	0.000	−6.102	0.627
	TP (mg/kg)	4.399	25	0.000	145.381	33.051
	C/N	0.45	25	0.656	0.871	1.934
	C/P	4.292	25	0.000	1270.918	296.097
	Soil moisture (%)	1.513	25	0.143	20.843	13.776
20–40 cm depth	Soil pH	−2.003	25	0.056	−0.262	0.131
	BD (kg/m ³)	0.293	25	0.772	14.741	50.249
	TOC (g/kg)	−27.278	25	0.004	−138.183	5.066
	TN (g/kg)	−6.712	25	0.000	−5.344	0.796
	TP (mg/kg)	−4.522	25	0.000	−42.721	9.446
	C/N	−0.933	25	0.360	−1.417	1.519
	C/P	−2.676	25	0.013	−1716.142	641.288
	Soil moisture (%)	−1.116	25	0.275	−13.453	12.052

Note: Δ = farmland mean – wetland mean. Negative Δ values indicate a decline after conversion. Δ values are presented separately for each soil depth. Cross-site comparisons of Δ were performed within each depth layer using independent samples *t*-tests; no between-depth comparisons were made. Number of independent samples: Jinchuan *n* = 5 per land use per depth; KVFP *n* = 4 (wetland) and *n* = 8 (farmland) per depth.

4. Discussion

4.1. Agricultural Conversion Induces Widespread Degradation of Wetland Soil Properties

In the past three decades, our land use change analysis reveals contrasting trajectories: Jinchuan Peatland experienced only minimal additional conversion, whereas the KVFP lost 28% of its wetland area, and its agricultural land expanded by 31% (Table 3). These trends are consistent with the different stages of food security and policy development in the two countries. China has achieved food security and enacted strict wetland protection laws, effectively halting reclamation [27]; Tanzania, facing ongoing food deficits and population pressure, continues to rely on wetland conversion for agricultural expansion [20,28]. These divergent development contexts, rather than hydrological factors alone, underlie the differing conversion rates observed.

Agricultural land use change has affected wetland soil properties. In this study, results showed that agricultural land use change influences soil carbon and nitrogen content in wetland ecosystems. TOC and TN significantly decreased in both soil depths across study sites (Table 4, Figures 4 and 5). Our data show a significant decline in TOC following wetland conversion at both sites (Figures 4 and 5). This finding is consistent with previous studies suggesting that cultivation reduces physical protection of organic matter, accelerates biomass removal, and promotes faster TOC decomposition and mineralization rates [29]. Similarly, the concurrent decline in TN observed in our data aligns with the well-documented coupling of carbon and nitrogen dynamics in soils; previous research has reported that removal of natural vegetation can result in substantial nitrogen losses from the soil system [30,31]. In addition to biomass removal, nutrient losses from agricultural soils may also occur through increased mobility and leaching, as noted in other studies [32]. Our observations of declining TOC and TN are broadly consistent with findings from other wetland ecosystems that have undergone agricultural conversion [33,34].

In Jinchuan Peatland, C/P ratio of agricultural land significantly decreased compared to wetland in both soil depths (Figure 4), whereas in KVFP, soil moisture and C/P ratio

dramatically decreased in both soil depths when wetland changed to agricultural land (Figure 5). Our data further show that in Jinchuan Peatland, the C/P ratio of agricultural land decreased significantly compared to wetland in both soil depths (Figure 4), while in KVFP, both soil moisture and C/P ratio decreased significantly in both layers following conversion (Figure 5). The decreased C/P ratio in agricultural soils at both sites is consistent with the interpretation that long-term application of nitrogen and phosphorus fertilizers, combined with the lower mobility of phosphorus relative to nitrogen in soil, tends to reduce C/P ratios in cultivated land uses [35]. Anthropogenic activities leading to land use change in wetland areas might alter soil C and N levels, affecting carbon and nitrogen cycles at regional or global scales. Moreover, loss of TOC due to wetland degradation may release additional CO₂ into the atmosphere [36], contributing to climate change and global warming. Conversion of wetland to agricultural land, associated with drainage for agricultural production, has caused declines in soil carbon and nitrogen, which may affect land productivity [37]. Furthermore, there was significant increase in soil pH and BD in both soil depths in both study sites when wetland changed to agricultural land. Soil under agricultural land had higher BD and pH compared to adjacent soils under wetland. Higher BD in agricultural land is attributed to machinery use in farming processes, which reduces soil agglomeration and increases BD [38]. Intensive farming also increases BD due to compaction.

It is worth noting that the markedly lower absolute BD values in Jinchuan Peatland compared to KVFP reflect the fundamentally different parent materials: Jinchuan is a histosol (organic-rich peat, >40% organic matter) with characteristically low bulk density, whereas KVFP soils are mineral alluvial soils with inherently higher bulk density. The significant increase in BD following agricultural conversion at both sites (Figures 4 and 5, Table 4) thus represents a comparable relative trend, despite the large absolute differences between the two soil types. These baseline pedological differences mean that direct comparisons of absolute TOC and TN declines between the two sites should be interpreted cautiously. To complement the absolute change comparison, we calculated the relative (%) change from the reference wetland state for each soil property. In the 0–20 cm layer, TOC declined by 56% in Jinchuan versus 73% in KVFP relative to their respective wetland baselines, while TN declined by 54% in Jinchuan versus 66% in KVFP. Thus, although the absolute TOC and TN losses were numerically larger in Jinchuan, the proportional loss was actually greater in KVFP. This apparent paradox—larger absolute loss in the peatland but larger relative loss in the floodplain—stems from the much higher initial TOC and TN stocks in the peat soil and highlights the importance of considering both absolute and relative metrics when comparing systems with contrasting baseline soil properties. The significant absolute declines observed in Jinchuan, even if proportionally smaller, remain ecologically concerning given the exceptional carbon density of peatlands.

4.2. Hydrological Replenishment Regime Influences the Magnitude of Soil Degradation After Conversion

Based on water supply source, wetlands can be classified into rain-fed wetlands, surface water inflow wetlands, groundwater discharge wetlands, and ice/snowmelt water wetlands [39]. Previous research has demonstrated that the hydrological regime exerts a profound influence on soil carbon and nitrogen cycling in wetlands, with drought conditions significantly promoting the release of carbon and nitrogen [40]. Our results extend this understanding by showing that the hydrological regime not only affects biogeochemical cycling under natural conditions but also modulates the magnitude of soil degradation when wetlands are converted to agriculture. Our data reveal a clear quantitative difference between the two sites: in the 0–20 cm layer, TOC and TN declined by 271.42 g/kg and 8.53 g/kg, respectively, in Jinchuan, compared to 48.03 g/kg and 2.42 g/kg in KVFP

(Table 4). We attribute this marked difference primarily to the contrasting hydrological regimes. The KVFP, as a flood-fed wetland, continues to receive alluvial sediment inputs even after parts of it are converted to agriculture; these periodic floods deposit nutrient-rich sediments onto agricultural fields, and previous studies have shown that such inputs can partially compensate for nutrients removed by crop harvest and lost through enhanced mineralization following drainage [41,42]. In contrast, the rain-fed Jinchuan Peatland relies entirely on precipitation for its water supply and no longer receives any external nutrient subsidies through surface or groundwater pathways, as detailed in Section 2.1.1.

The differential changes in C/P ratios between the two sites provide additional support for this interpretation. Our data show that in KVFP, the C/P ratio in the 20–40 cm layer increased after conversion, whereas in Jinchuan it decreased (Table 4). We suggest that the increase in KVFP may reflect the input of phosphorus-poor alluvial sediments, consistent with the flood-replenishment mechanism outlined above, while the decrease in Jinchuan is consistent with phosphorus accumulation from fertilizer application in the absence of external carbon replenishment, as described in previous fertilization studies [35]. The concept of wetland resilience to agricultural disturbance remains underexplored in the literature. Our findings suggest that flood-fed wetlands possess a form of natural buffering capacity through continued nutrient replenishment, which partially mitigates the degradation observed following conversion. Importantly, we emphasize that this does not imply immunity to degradation—our data clearly show significant declines in soil quality in KVFP as well (Figures 4 and 5). Rather, the degradation is quantitatively less severe compared to the rain-fed system. We propose that this insight has important policy implications for wetland management in food-insecure regions where some degree of wetland utilization may be unavoidable.

While the hydrological replenishment mechanism provides a coherent explanation for the differential degradation observed, we acknowledge that other factors may also contribute. First, the two sites differ fundamentally in soil type: Jinchuan is a peatland (histosol) with characteristically high organic matter content, whereas KVFP is a mineral alluvial floodplain. Organic-rich peat soils are known to be particularly susceptible to rapid mineralization upon drainage, as the lowering of the water table exposes previously anaerobic peat layers to oxygen, accelerating microbial decomposition and releasing large quantities of CO₂. This process, termed peat oxidation or peat subsidence, can independently explain a substantial fraction of TOC and TN loss in Jinchuan, irrespective of the absence of external nutrient replenishment. The mineral alluvial soils of KVFP, by contrast, have lower organic matter content inherently and do not experience the same magnitude of oxidation-induced carbon loss upon drainage. Therefore, the larger absolute TOC and TN declines observed in Jinchuan may partly reflect the inherent vulnerability of peat soils to drainage-triggered oxidation, rather than solely the lack of hydrological nutrient replenishment. Second, the duration of cultivation differs: approximately 30 years in Jinchuan versus 10 years in KVFP. Longer cultivation periods generally lead to greater cumulative TOC losses, and this difference could partially account for the more pronounced declines observed in Jinchuan. Third, differences in fertilization practices, crop management, and socioeconomic drivers—including China's shift toward conservation policies versus Tanzania's ongoing agricultural expansion—add further layers of complexity that cannot be fully disentangled in a two-site comparison. Future studies incorporating multiple sites per wetland type and a broader range of cultivation ages would be better positioned to isolate the effect of hydrology from these confounding variables.

In summary, our study demonstrates that agricultural conversion leads to significant soil degradation in both rain-fed and flood-fed wetlands, but the severity of degradation differs substantially between the two types. Specifically, our quantitative comparisons show

that declines in TOC and TN were consistently greater in the rain-fed Jinchuan Peatland than in the flood-fed KVFP, across both soil depths (Table 4). While acknowledging that multiple environmental and management factors beyond hydrology may contribute to these differences, the within-site paired design controls for soil type and climate at each location, and the systematic pattern of more severe degradation in the rain-fed system aligns with the mechanism of absent external nutrient replenishment. We therefore suggest that rain-fed wetlands, which lack nutrient inputs from flooding, are likely more vulnerable to agricultural conversion and should be prioritized for strict protection. For flood-fed wetlands in regions facing acute food insecurity, carefully managed utilization under appropriate farming intensities may represent a pragmatic strategy, although the sustainability of such use requires further long-term study, and maintaining the hydrological connectivity that underpins their relative resilience is essential.

4.3. Customize Wetland Management Methods According to Wetland Type and Hydrological Regime

This study has investigated and compared the effects of land use change on selected soil physical and chemical properties in Jinchuan Peatland, China, and KVFP, Tanzania. The study concluded that land use change in the two selected study areas is characterized by conversion toward agriculture land. Also, these agricultural land use changes have affected soil nutrient status and structural stability, causing reduced soil fertility and increased susceptibility to soil erosion. Consistent with previous findings in East African wetlands [10], TOC and TN in both Jinchuan Peatland and KVFP significantly decreased during the last 28 years, whereas soil pH and BD increased in both soil depths in KVFP—a pattern commonly associated with long-term agricultural disturbance [42]. However, there were no statistically significant changes in TP, soil moisture, and C/N ratio in both study sites. Moreover, comparison results of the two study sites found that the most dramatic effects were observed in TOC and TN of Jinchuan Peatland, which significantly declined more than in KVFP due to differences in farming methods and water supply mode. This illustrates the need to explore farming systems and water supply sources to wetlands, and to examine which is more favorably selected for agricultural conversion. In summary, wetland conversion to agricultural land may lead to loss of soil fertility and increased soil erosion, and the degradation degree of rain-fed wetlands is greater than that of flood-fed wetlands. To prevent this phenomenon from appearing or worsening, combined with the consequences of different farming methods and different types of wetland reclamation, the following points are put forward in wetland management:

Firstly, wetlands should be classified according to different types of water supply, and different types of wetlands should adopt different management systems. Management of rain-fed wetlands should be stricter than management of flood-fed wetlands. Secondly, different countries have different national conditions and farming methods, so they should adopt different management systems according to their situations and adapt to local conditions. Although grain yield from primitive farming methods in Tanzania is less than that from modern agriculture, the former has less impact on wetland hydrological cycles and less damage to soil structure from large agricultural machinery, so primitive farming methods do less damage to wetlands than modern agriculture. However, primitive farming methods still need further development and improvement to achieve sustainable agriculture that can provide more food production to meet the needs of Africa's growing population. Thirdly, after establishing a clear management system, targeted regulatory measures are needed to strengthen supervision and improve effectiveness. Lawless elements should be resolutely punished according to law, and dereliction of duty in supervision should be strictly accounted for. Ultimately, under a clear management system, wetland ecosystems can develop in a healthy and orderly manner.

4.4. Novelty and Comparison with Previous Studies

This study provides several novel contributions beyond existing literature. First, while previous studies in China have examined wetland conversion effects on soil properties [4,12], most focused on a single wetland type or a single country. Our cross-national comparison of two hydrologically distinct wetlands is, to our knowledge, the first to directly compare rain-fed and flood-fed systems under contrasting national development contexts. Second, within Tanzania, earlier work in the Kilombero Valley documented land use change but did not quantitatively compare soil degradation between flood-fed and rain-fed systems [10,20]. Our study extends these findings by introducing a resilience framework based on hydrological replenishment. Third, our dual-metric approach (absolute + relative change) addresses a common methodological challenge when comparing organic and mineral soils. Finally, by explicitly linking hydrological connectivity to soil functional resilience, this study offers a mechanistic hypothesis that can be tested in other wetland systems. Compared with previous work in Chinese peatlands [12,26], our study is the first to explicitly attribute differential degradation to the absence versus presence of alluvial sediment inputs, rather than to management practices alone.

5. Conclusions

By comparing a rain-fed peatland in China (Jinchuan) with a flood-fed floodplain in Tanzania (KVFP), this study reveals differential soil degradation following agricultural conversion: declines in soil organic carbon and total nitrogen were consistently more severe in the rain-fed system than in the flood-fed system. These findings are consistent with the hypothesis that hydrological replenishment—particularly the continued input of alluvial sediments in flood-fed wetlands—can partially buffer soil fertility loss, whereas rain-fed wetlands, lacking such external nutrient subsidies, are more vulnerable to degradation. However, we emphasize that this study is based on only two environmentally distinct sites, and the observed differences may also reflect other site-specific factors such as inherent soil properties, climate, and management history. The role of hydrology, while strongly supported by the within-site paired design, should be viewed as one important contributing factor rather than the sole determinant. Further research across a wider range of wetland types and geographic settings is required to test the generality of these patterns and to disentangle the effects of hydrology from other confounding variables.

From a policy perspective, our results suggest that wetland management strategies would benefit from considering hydrological type. Rain-fed wetlands appear to be more sensitive to agricultural conversion and may warrant stricter protection. Flood-fed wetlands, in contrast, may offer opportunities for carefully regulated agricultural use in regions facing acute food insecurity, provided that the hydrological connectivity that delivers sediment-bound nutrients is maintained. Nevertheless, such utilization strategies must be informed by local environmental assessments and long-term monitoring and should not be interpreted as a blanket endorsement of flood-fed wetland conversion.

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Abbreviations

The following abbreviations are used in this manuscript:

KVFP	Kilombero Valley Floodplain
LUC	Land use/cover
SOC	Soil organic carbon
BD	Bulk density
TN	Total nitrogen
TP	Total phosphorus

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