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Developing an indicator for assessing wetland degradation based on soil quality, water drainage, and human-related landscape factors

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ABSTRACT

Due to environmental stress and anthropogenic pressures, wetlands are declining and being degraded in areas with increased settlement and road construction. Although various indicators have been developed to assess ecosystem degradation, few studies have specifically addressed wetland soil degradation and its underlying drivers. In this study, we attempted to create a Wetland Soil Degradation indicator (WSDI) and identify its driving factors in a contrasting landscape characterized by significant anthropogenic changes. We selected the eastern Democratic Republic of Congo (DRC), a region where severe wetland degradation primarily caused by agriculture and brickmaking activities has been reported. We combined Geographic Information System (GIS), remote sensing approaches and soil profile analysis. For landscape change, four concentric circles from the two wetland centers were made. A WSDI was developed and refined using the minimum data set (MDS) coupled with multivariate statistical techniques to assess the level of wetland degradation. For the case study, an overall WSDI score averaged 0.52 across the two sites. Higher degradation was observed in brickmaking (0.62) compared to agriculture zones (0.52), while intact zones had a lower score (0.28). Degradation was also more severe in completely drained areas (0.72) than in partially (0.48) and intact, non-drained areas (0.28). Significant correlations were found between the level of degradation and human-related landscapes, notably the proximity to villages, rural settlements, and roads. Wetland degradation was strongly linked to road accessibility and the distance to human-related landscapes. The indicator confirmed a gradual degradation pattern, starting from the wetland edges and moving toward the center. Overall, the WSDI is essential for diagnostic purposes before developing a restoration plan to ensure sustainability and to question these critical ecosystems' future.

1. Introduction

Wetlands are areas of land where soils are saturated with water, either permanently or seasonally. These ecosystems are characterized with waterlogged condition, with soils developed under water saturated conditions allowing development of vegetation adapted to water saturated conditions. Their ecological and societal benefits are well established; however, in recent years, severe degradation and losses have been reported in many parts of the world (Moomaw et al., 2018; Hambäck et al., 2023; Kundu et al., 2024).

Wetland degradation is a global concern in the 21st century, particularly in tropical and subtropical regions, although significant losses have been observed in Europe and Asia (Hu et al., 2017; Fluet-Chouinard et al., 2023). It involves the physical, chemical, and biological degradation of wetland soil. Physical degradation includes susceptibility to compaction, waterlogging, and chemical leaching, while chemical degradation encompasses acidification, salinization, and nutrient depletion. A decline or reduction in soil organic matter (SOM) and flora indicate biological soil degradation (Chen et al., 2022; Howe et al., 2023; Jiang et al., 2024). The combination of these three types of degradation leads to ecosystem deterioration, affecting their capacity to provide essential functions and services, mainly supporting plants and animals, while creating environmental stress with higher effects on humans (Lal, 2001, 2007; Nath & Lal, 2017). Given the magnitude, particular attention is increasingly being directed toward these wetland areas.

Wetland soil fulfills multiple sociological and ecological functions, among which productivity, stability, and nutrient storage are essential. With wetland fragmentation and degradation, these functions regress or disappear. From an agronomic perspective, most research primarily

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focuses on soil productivity, often reflected through soil fertility, which is commonly emphasized in evaluations. Fertility-based soil quality indices have been developed and appreciated for their simplicity, sensitivity, and flexibility. These indices generally involve selecting suitable indicators, transforming them into scores, and combining these scores into a comprehensive index. While such indices yield satisfactory results for fertility assessments due to their credibility and practicality, they often neglect other essential functions of wetland soils (Rokosch et al., 2009; Wang et al., 2018; Zhang et al., 2022). Various external factors may constrain these functions, which rarely interact with indicator development, given the complex relationship between wetland soil function and their driving factors. Therefore, establishing a scientific approach is necessary to assess wetland degradation comprehensively and better understand wetland soil health (Wang et al., 2018).

Several studies have developed indicators of wetland quality, ranging from animal and plant species and soil and water quality to fieldwork and remote sensing. These studies continue to grow, increasingly integrating new approaches and innovations (Kantrud & Newton, 1996; Goslee et al., 1997; Pollet & Bendell-Young, 2000; Rokosch et al., 2009; Cvetkovic & Chow-Fraser, 2011; Sims et al., 2013; Darrah et al., 2019; Herlihy et al., 2019). Unfortunately, studies that integrate direct drivers of wetland degradation and human-related landscapes in a local context-dependent are limited. Other drivers, such as water drainage system, type of use, and human-related landscape, are lacking and mostly not incorporated in these evaluations. Furthermore, several studies have demonstrated that biodiversity regulates various ecological functions necessary for maintaining wetland productivity and efficiency. It remains uncertain how human activities affect directly the "multifunctionality" of wetlands and how, indirectly they influence the biodiversity that governs their ecological functions (Hambäck et al., 2023).

Few available studies have shown that water exploitation and accessibility lead to wetlands degradation (Schuyt et al., 2005; Mitchell et al., 2022; Mirenge et al., 2023). Unfortunately, these studies are often focused on land-use dynamics using remote sensing indices. Other use physicochemical proprieties to create soil quality indices (SQI) (Wang et al., 2018; Cvetkovic et al., 2019; Shen et al., 2019; and Zhang et al., 2022). However, these indices are developed using the Minimum dataset (MDS) approach to evaluate soil quality. Although MDS is appreciated and under development, certain limitations are nonetheless raised (Arshad and Martin, 2002; Drobnik et al., 2018). Since wetland degradation influences soil quality, it's the prediction in terms of quality remains not well understands and developed in different landscapes. Furthermore, its application to determine the effects of wetland types of use, water management through drainage, human accessibility, and landscape change is still also clearly understand as the reliability of such indices is questioned when applied to a different local context from where they were developed (Wang et al., 2018; Zhang et al., 2022).

This study focuses on rural wetlands in the eastern Democratic Republic of Congo (DRC), where significant anthropogenic pressures have been reported (Chuma et al., 2021; Nacishali et al., 2024). Three major drivers are highlighted: land-use changes, excessive utilization through agriculture, livestock, and brickmaking activities. Wetlands are primarily converted into agricultural areas, biomass harvesting sites for fodder or other domestic uses, and brickmaking zones. Others are fishing and washing minerals in small-scale operations (Chuma et al., 2022). Brickmaking involves stripping away the organic topsoil (or peat) to reach clay-rich horizons used for brick production. This process includes soil excavation, vegetation destruction for brick coverage, and deforestation for fuel during brick firing. As agriculture and brickmaking are major drivers of wetland degradation in this region and in other parts of the sub-Saharan region, it is essential to examine their impact on wetland soil degradation. Wetland soil degradation refers here to the loss of capacity of wetland soils to function within natural or managed ecosystem boundaries, not to sustain plant life, and not to support human health and habitation. Such a definition seems essential for understanding the issue of wetland degradation.

One notable observation is that no existing indicators in the literature are adequately considered or available to assess the degradation level of wetlands in the local context of the region (Cvetkovic and Chow-Fraser, 2011; Wang et al., 2018; Shen et al., 2019; Zhang et al., 2022). Physical and chemical indicators offer crucial information on soil degradation, while soil erosion, habitat fragmentation, and land-use changes, such as conversion and development to agriculture, significantly impact wetland function. Chemical indicators, such as nutrient enrichment and pollutants, degrade water quality and harm aquatic life (Mirenge et al., 2023). By carefully monitoring these indicators, scientists and environmental managers can track wetland health and implement timely interventions to prevent further degradation and promote long-term sustainability. In eastern DRC, indicators of wetland degradation are less studied than in other ecosystems such as dense, Miombo or mountainous forests. Although the services wetlands provide to millions of people in high-poverty areas, these ecosystems are under significant natural and anthropogenic pressure (Tyukavina et al., 2018; Molinario et al., 2020; Bernard et al., 2023; Nacishali et al., 2024).

To address such a gap, we propose developing a wetland degradation indicator that accounts for the aforementioned local context by combining different data types and approaches. Firstly, we aim to provide an overall assessment of the current state of the wetlands selected as case studies and evaluate the degradation level based on the MDS approach. Secondly, assess the impact of anthropogenic activities, mainly agriculture and brickmaking, on the degree of degradation. Lastly, we evaluate the effect of human-related landscapes on wetland degradation based on the developed indicators.

2. Methodology

2.1. Study area

Two wetlands were selected as case studies to develop the wetland degradation indicator. They were selected based on their accessibility and data availability. In these two wetlands, the expansion of both agriculture and brick-making activities are observed making them relevant case studies for illustrating the current state of wetlands in eastern DRC. They are located in the South-Kivu province in eastern DRC (Fig. 1). The province has a high diversity of wetlands, ecosystems that cover ~ 13.5 % (898,690 ha) of the province's total area of ~ 64,791 km2. Agriculture is the dominant activity in the region, alongside other artisanal activities such as mining, trade, and brickmaking. The province also benefits from a wide range of biophysical conditions, making it rich in biodiversity and offering strong agricultural potential (An Ansoms and Win Marivoet, 2010). However, it remains one of the areas experiencing significant anthropogenic pressures, primarily due to the high density of population observed in the region, similar to the entire African Great Lakes region (Asefi-Najafabady et al., 2018; Sietchiping et al., 2018).

The two wetlands are located at high altitudes, specifically in Karhongo, Nyangezi, Lucinga (Nalugana), and Namumve within the Kabare territory. These areas are mainly characterized by hygrophilous grassy species, shrubs in intact zones, followed by agricultural fields, primary vegetable crops, and sometimes rice paddy and sorghum. Other parts are cleared due to brickmaking activities. Tiny houses and wooded patches are found in small portions. These wetlands serve as typical examples for understanding the level of degradation in the eastern DR Congo, with a focus on human-related driving factors (Fig. 1).

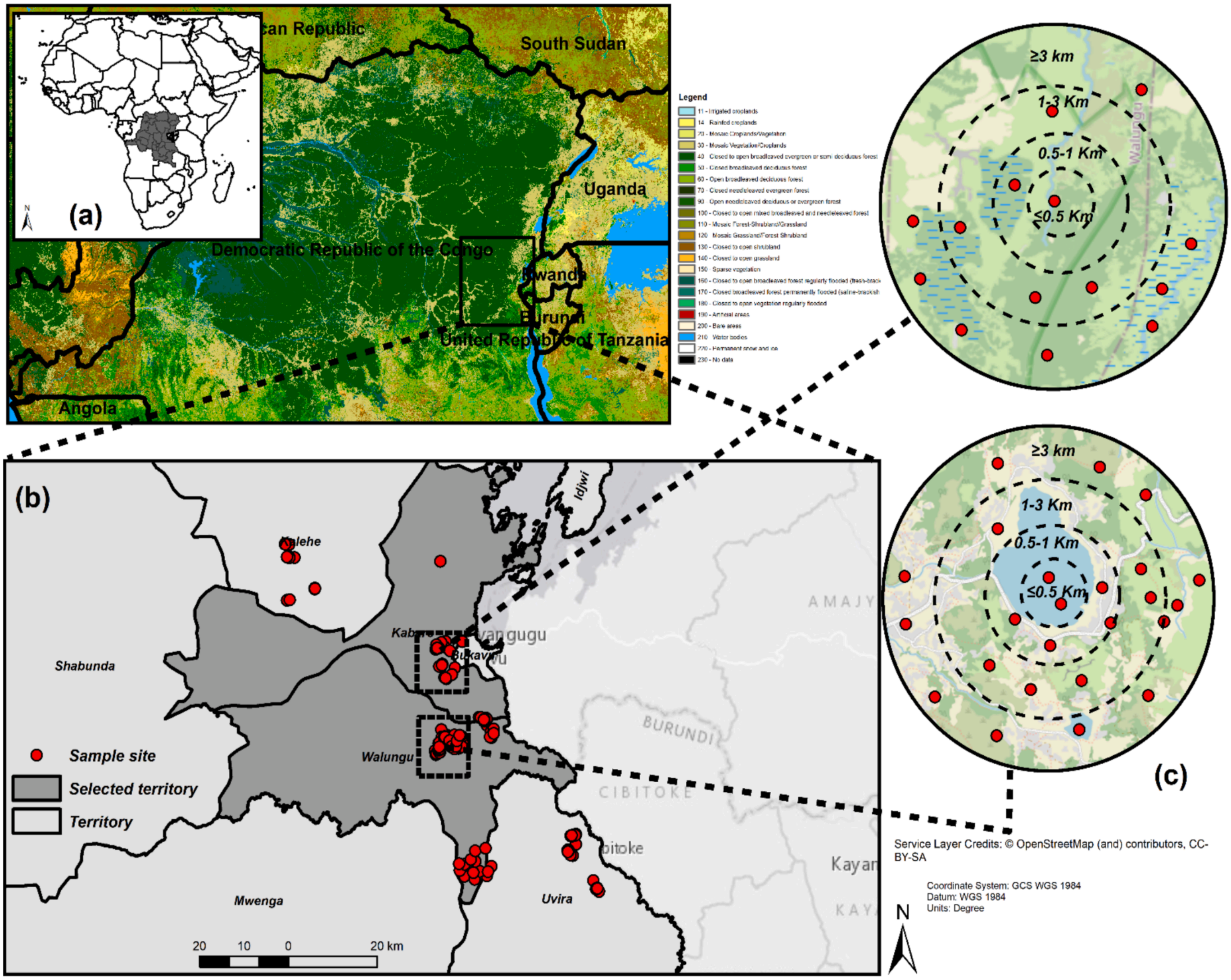

Fig. 1. Location of the study area in South-Kivu, eastern D.R. Congo. Sampling locations in the wetlands area (red dots) (b), associated with the four radius circle from the center of wetlands to the border (≤0.5 km, 0.5–1 km, 1–3 km; and ≥ 3 km).

2.2. Field investigation and soil sampling

First, we used previously produced data from Chuma et al., (2023) to determine each selected wetland's surface area and perimeter. We used available land use and land cover data from the "*Observatoire Indépendent des Forets et Paysages Montagneux*" and the FAO land use map to assess the spatial dynamics within and around each wetland. These maps were confirmed using the analysis made in section 2.3.

Finally, satellite images were used for current data to ensure that all land use types were accounted for. Secondly, the developed approach first involved identifying the geographical coordinates of the center of each wetland and its extent. Circles with a 200-m radius were generated from the wetland center. After, four classes of radius-circles were considered: central (≤0.5 km), medium closer (0.5–1 km), far (1–3 km), and very far (≥3 km). Since the two wetlands are rather fusiform (longer than wide), the distances were calculated along the length of the wetlands.

To ensure that all land-use classes and random effect were integrated, we generated random points around the wetland areas, using the largest circle (≥3 km) as the boundary. For analysis, three replications were randomly considered for each point. Based on previous studies (Chuma et al., 2022; Mirenge et al., 2023) and the land use analyses from available images, three land-use classes were considered: *brickmaking areas, agricultural fields*, and *intact zone* with no human activities. Regarding drainage, three categories were identified: *not drained* or *intact zones* and *partially* and *completely drained zones*. Points were selected to ensure that these three factors are taken into account. One hundred eight points were selected to ensure factor representation, with twenty seven points per radius circle. At each point, soil samples were collected from the root depth (~30 cm) using a soil auger. The samples (minimum 500 g for each) were conditioned and sent to the laboratory for pedological analyses. The field works took place from January to February 2024 while laboratory analysis ended in November 2024; 14 elements were analyzed as detailed in the section 2.4.

2.3. Remote sensing

We integrated remote sensing to better characterize land use and understand the impact of human activities on wetlands. First, satellite images were downloaded and georeferenced to assess land use and cover within and around each wetland zone. The results from these images were compared to other, as previously mentioned. We created a script to analyze the evolution of land use and land cover for each zone following the NDVI and NDWI calculated using Sentinel-2A (UTM MGRS tiles: 35MPR and 35MQP) of 10 m resolution. The formula as used and developed by Mack (2006) and Muro et al., (2018) were used. The period from 2020 to 2024 was considered. This allowed us to confirm the different land uses and their evolution. Four factors were considered to evaluate the impact of human activities on the landscape around wetlands. These included the distance to human-related landscape elements. Studies have shown that ecosystem accessibility is a major driver of degradation (Shen et al., 2019; Kundu et al., 2024; Nacishali et al., 2024). Therefore, the distance to nearby villages, schools, and churches was calculated to assess the impact of human-related landscapes on degradation. Additionally, the distance to the area's main road, market, and primary river was included. These elements were considered due to their role in exporting products from the wetlands or providing inputs, labor, and other resources. Spatial analysis in ArcGIS 10.7 Esri-TM was used to calculate and produce distance maps for these elements, and the values for each point were extracted accordingly.

2.4. Soil analysis

The sample collected during fieldwork was analyzed in the College of Agricultural and Environmental Sciences (CAES) laboratory of the Makerere University in Uganda. Both physical and chemical analyses were made. For soil texture, the Bouyoucos hydrometer method (Bouyoucos, 1936) was used after pre-treatment with H_2O_2 to remove soil organic matter (SOM). A USDA textural triangle was used to determine the textural classes. Soil acidity was measured using a Hanna pHmeter at a 1:5 soil–water ratio. Soil carbon content was analyzed using the Walkey and Black method (Walkley & Black, 1934). Phosphorous using the Olsen method and total nitrogen using the Kjeldahl method. The conversion of soil organic carbon (SOC) to soil organic matter (SOM) was calculated using the factor 1.724 as suggested by Van Bemmelen (Minasny et al., 2020). Available K^+, Ca^{2+}, Mg^{2+}, and Cation exchange capacity (CEC) were analyzed using NH_4OAc, 1 N at pH:7 according to Chapman protocole (Chapman, 1965). Al^{3+} and Fe^{3+} were analyzed following the atomic absorption spectrophotometer as suggested by Okakebo et al., (2002).

Table 1 describes the descriptive statistics of the soil parameters that characterize wetland soil samples. The results show that the wetland soils had a CEC of 14.54 Cmol/kg, with a minimum value of 7.4 and a maximum of 30.4 Cmol/kg. Significant variability in bulk density was observed between soils, ranging from 1.02 to 1.43 g cm^{-3}. The texture was classified as clayey according to the USDA triangle, with clay content exceeding 58 % and reaching up to 89 %. The soil wetland soil was highly acidic, with a current pH of 5.1 and a total pH of 3.8. The exchangeable acidity (the difference between pH-water and pH-KCl) was higher on average at 1.3. Exchange acidity, a crucial component of soil fertility, indicates the amount of acidic cations (primarily $H^+ + Al^{3+}$) and reflects the availability of nutrients. It also contributes to the disintegration of soil aggregates, reducing porosity and water retention. The high value confirms the acidic base cations in the soil solution. According to SOM, on average, these wetland soils are very rich in OM, ranging from 5.8 % in minerogenic zones to 76 % in histosols sites (Table 1).

2.5. Indicator creation

In order to evaluate, monitor, and communicate complex phenomena such as wetland soil degradation, a structural approach based on the indicator system framework was selected. This method consists of three steps: fieldwork for measurement and quantification of available data, calculation and scale of the indicator, and analysis. The creation of an indicator involves reducing the dimensions of variables. Here, we proposed to merge different soil parameters, accessibility and drainage, and create new variables with more details. Eight indicators were calculated first and then integrated to create the final Wetland Soil Degradation Index (WSDI). These indicators include erodibility, structural stability, soil fertility, carbon storage, distance to nearest human activities, and drainage appreciation. According to the physical properties of wetland soil, we use the soil structural stability index (SSSI) as suggested Awoonor et al., (2024) to assess the soil stability. The formula (i) was used to determine the SSSI. The second characteristic was soil erodibility, which assessed the sensitivity to erosion by the erodibility-modified clay ratio (eMCR) (ii). The third was the critical level of SOM and susceptibility to erosion (CSOM). eMCR and CSOM (critical level of soil organic matter) were determined following the formula (ii) and (iii) (Zahedifar, 2023; Awoonor et al., 2024).

For accessibility and drainage, we first calculate and integrate the distance from the sample point in the wetland to the nearest market (distance to market: DTM), road (distance to road: DTR), villages (distance to homes: DTH), and river (Euclidean distance to river: EDR). After the values were standardized following the formula (*v*) and (*vi*). At each point, centroid grids were made (as shown in section 2.3 and Fig. 1). At the same time, land use was extracted for each centroid, and the dominant land-use at the sample site was determined and affected to the coordinate of the sample point. The buffer zones represent the circle from the center to the limit of the water. They comprise the waterward radiation zone, the water level variation zone, and the landward radiation zone. Only three classes (agricultural zones, brickmaking zones, and intact zones) were considered.

The soil degradation index (SDI) is linked to fertility due to plant nutrient availability. It is a quantitative metric designed to assess the extent and mostly the severity of soil degradation across various sites and landscape. It is obtained in integrating multiple soil proprieties to evaluate change in soil quality based mainly on nutrient (macro and micro) availability to plants. We used the soil proprieties as suggested by Wubie et al., (2020) and Lal (2007). These variables are available in the **Table S3 and S5**.

SDI is similar to the soil fertility index (SFI) as previously developed by Mujiyo et al., (2022); locally called degradation vulnerability potential (DVP), was estimated following the formula (iv) developed by Lal (2007) where pH, CEC, N, P, and K, Fe, MO, were mixed and weighted assigned following the PCA.

Table 1
Descriptive statistics of the characteristics of the selected points in the wetlands.

Variables	Units	Mean	SD	Mode	SE	Kurstosis	Skweness	Range	Min	Max
CEC	Cmol/kg	14.54	0.33	11.30	3.90	3.42	1.44	23.00	7.40	30.40
BD	g. cm^{-3}	1.20	0.01	1.18	0.06	2.52	0.81	0.41	1.02	1.43
Al^{3+}	ppm	0.18	0.00	0.20	0.04	1.45	−1.48	0.20	0.10	0.30
K^+	g kg^{-1}	0.25	0.01	0.18	0.16	6.94	2.39	0.96	0.10	1.06
Fe^{2+}	ppm	2.22	0.04	2.46	0.50	−0.39	0.39	2.16	1.29	3.45
TN	%	2.26	0.05	2.15	0.58	−0.57	0.11	2.61	0.98	3.59
Silt	%	28.42	0.30	29.70	3.53	−0.25	0.02	16.70	20.80	37.50
Sand	%	5.41	0.27	4.00	3.18	0.40	0.89	14.98	1.02	16.00
Clay	%	68.54	0.41	66.08	4.84	3.20	1.09	31.40	58.08	89.48
pH-KCl (1:5)	–	3.80	0.03	3.54	0.31	1.21	0.94	1.72	3.15	4.88
pH-H_2O (1:5)	–	5.11	0.02	5.20	0.26	0.93	0.97	1.30	4.70	6.00
SOM	%	33.04	1.78	19.14	20.83	−0.99	0.90	63.41	12.59	76.00
SOC	%	9.69	0.14	9.40	1.65	0.18	0.06	7.80	5.80	13.60

To support the theoretical basis of PCA-derived weights, component loadings were interpreted in light of literature and theoretical basis from Lal (2007). The explanation of each component was interpreted while weight stability was verified through a one-at-a-time sensitivity analysis. Monte Carlo simulation showed minimal shifts in ranking confirming the robustness and rationality of the values of weights assigned.

To adjust the SDI (TransSDI), the calculation of Nutrient index (Based on Soil index system) developed by USDA was used. This consisted of using a five classes scale (5: extreme, 4: severe 3: moderate, 2: slight, and 1: none) and normalization of the index from (0 to 1) using (v).

The adjusted SDI can be understood as the soil degradation based on the nutrient availability for sustainable plant growth, which is based on the level of soil nutrient richness. Here, we only considered 7 nutrients (Table 1**)** for calculation.

$$\boldsymbol{SSSI} = \frac{1.724 \times \boldsymbol{SOC}(\%)}{\boldsymbol{Clay}(\%) + \boldsymbol{Silt}(\%)} \times 100 \quad (1)$$

$$\boldsymbol{eMCR} = \frac{(\%\boldsymbol{Sand} + \%\boldsymbol{Silt})}{\%\boldsymbol{Clay} + \%\boldsymbol{SOC}} \quad (2)$$

$$\mathbf{CSOM} = \frac{\boldsymbol{SOM}}{[\boldsymbol{CLAY}\% + \boldsymbol{SILT}\%]} \quad (3)$$

$$\boldsymbol{SDI} = \sum_{i=1}^{n} \alpha_i \times \boldsymbol{NI}_i \quad (4)$$

Or

$$\mathrm{SDI} = \alpha_1 \times \mathrm{NTK} + \alpha_2 \times \mathrm{P} + \alpha_3 \times \mathrm{K} + \alpha_4 \times \mathrm{pH} + \alpha_5 \times \mathrm{CEC} + \alpha_6 \times \mathrm{Fe} + \alpha_7 \times \mathrm{MO}$$

Legend: SDI: soil degradation index, TransSDI: transformed SDI, NI: nutrient, CSOM: critical level of soil organic matter, SSSI: soil structural stability index, eMCR: erodibility modified clay ratio. Calculation of Nutrient index is based on the Soil index system developed by USDA (See Supplementary Table S3*), SOM: soil organic matter, SOC: soil organic carbon. α the weighting coefficient, and Ni the nutrient i.*

2.6. Formula used to create and adjusted WSDI

To develop the wetland soil degradation indicator (WSDI), the flowchart in **Supplementary Fig. S4** was used. It consists of the combination of the minimum data set (MDS) and the statistical method (PCA). Initially, the physicochemical soil analyses were combined to create 4 indices and 4 for accessibility and drainage (Table 2). The MDS approach was normalized using two methods: (i) "*higher is better*" and (ii) "*lower is better*", depending on whether a higher value was considered "*good*" or "*bad*" in terms of soil fertility and quality based on the standardization formula (vi) and (vi). Indeed, the non-uniformity of indicator dimensions requires standardization to facilitate combination and comparison. In effect, min–max standardization was used for both variables mentioned above. We continued in performing a principal component analysis (PCA) on data extracted from the MDS. The primary idea behind the PCA was to reduce the number of indicators (if possible) while retaining information; whereas, MDS is used to reduce dimensionality within the database. Three principal components (PCs) with an eigenvalues greater than 1 were assumed to represent significant variability and selected for identifying high factor loadings. For each PC, a loading was associated with each variable. WSDI was obtained with the weighted methods of the selected variables using the formula (vii) and (viii). The weighted method is a linear combination scoring function, and the variables scoring used weight factors for computation. Wetland degradation analysis was divided into three steps: firstly, a wetland soil degradation index (WSDI) was established, and then used to understand the degree of degradation, finally the spatial autocorrelation method and integration of interference of human activities were used to grasp the spatial trend of wetland degradation.

$$\textbf{Positive indicator}: \mathbf{z_i} = \frac{\boldsymbol{x_i} - \boldsymbol{min}(\boldsymbol{x})}{\boldsymbol{max}(\boldsymbol{x}) - \boldsymbol{min}(\boldsymbol{x})} \quad (5)$$

$$\textbf{Negative indicator}: \mathbf{z_i} = \frac{\boldsymbol{max}(\boldsymbol{x}) - \boldsymbol{x_i}}{\boldsymbol{max}(\boldsymbol{x}) - \boldsymbol{min}(\boldsymbol{x})} \quad (6)$$

$$\boldsymbol{WSDI} = \sum_{i=1}^{n} \boldsymbol{W_i} \times \boldsymbol{I_i} \quad (7)$$

$$\boldsymbol{adj} - \boldsymbol{WSDI} = 1 - \boldsymbol{WSDI} \quad (8)$$

Legend: *WSDI: wetland soil degradation index, n: number of individuals, W: Weight and I: the individual parameter. The weight factor for indicators is calculated as the percentage of variance explained by all the PCs with eigenvalues divided by the total percentage of variation.*

Finally, the normality of the WSDI was tested using the Shapiro-Wilk test. Since the data did not follow a normal distribution, it was adjusted using the formula (viii). WSDI obtained was adjusted to [0,1]. The adjusted-wetland soil degradation index (adj-WSDI) is a new proposal for quantifying wetlands' pedological function and capacities and their degradation level by human activities. Its estimation is based on the principle of "*less is better*" and the midpoint "*optimum*", i.e., the higher the value of adj-WSDI, the worse the soil quality. The final WSDI (after adjustment) varied from 0 to 1 and reclassified in three classes. The classification made by discretization combined with suggestion in literature (Chen et al., 2022), three classes were maintained: values ≤ 0.4 were considered as *undegraded* or *slightly* degraded, while those between 0.4–0.70 were classified as *moderate* to *severe* degradation. Once the value exceeded 0.7, the degradation was considered *hig*h or e*xtreme* (Darrah et al., 2019; Chen et al., 2022). The flowchart used to obtain the index is presented in the **Supplementary Fig. S3**.

2.7. Relationship between the wetland soil degradation and interference of human activities

To highlight the human-related landscape as the interference of human activities and the created adj-WSDI indicator correlation and linear models were executed between adj-WSDI and DTM, DTR, DTH, and EDR. A Spearman's correlation analysis was conducted for all the variables. As nonlinear relationships were observed between adj-WSDI and certain variables, we proposed using a nonlinear model. The Generalized additive model (GAM) was adopted due to its robustness and its ability to handle spatial data without imposing a fixed functional form between variables. The method uses a link function to capture the relationship between the expectation of explained variables and nonparametric explanatory variables (Feng et al., 2018). A smoothing function (splines) was also applied for visualization purposes. The GAM also allows for a clear interpretation of the individual effect of each factor on the adj-WSDI variable. Several model types were tested, and the one retained is presented in Supplementary **Table S5**. We used Akaike information criterion (AIC) to select the appropriate model with different explanatory variables. We also used F-statistic and p thresholds to evaluate the significance of each factor. The summary of all the other models is presented as **Supplementary material 1**.

To analyze the spatial autocorrelation of the adj-WSDI, the Moran's I was calculated using ArcGIS 10.7 Esri-TM. Moran's I helped to assess the spatial distribution of the wetland degradation phenomena. The statistical analysis was executed in RStudio and R 4.2.1. The packages "*ggplot2*″, "*vegan*", "*factoextra*", and "*ggpairs*" were used for graph creation and analysis.

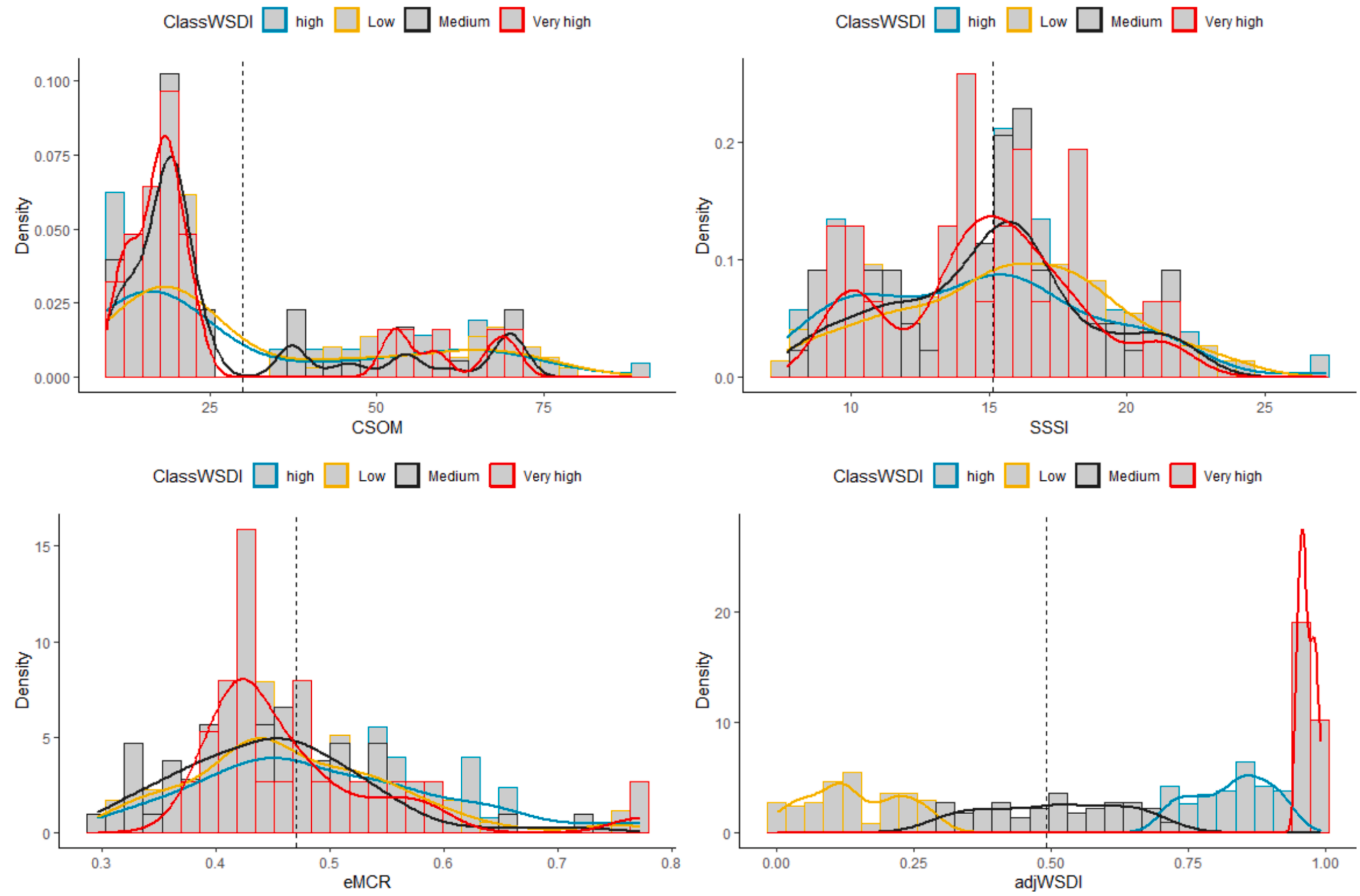

Fig. 2. Histogram and density plot of the four indicators developed to assess the wetland degradation in eastern DR Congo.

3. Results

3.1. Description of the indicator components

We first analyzed the distribution of the indicators developed (Fig. 2) and then conducted descriptive statistics (Table 2). The results indicate that the SSSI has an average value of 15.4, ranging from 8.3 to 27.25. On the other hand, the CSOM averages 30.6, with a wide variability ranging from 10.6 to 88. The erodibility index, related to eMCR, has an average value of 0.46, with maximum and minimum values of 0.77 and 0.30 respectively. In contrast, the soil fertility index (SFI) averages 0.35, with values ranging from 0.0 to 0.98, indicating the existence of nutrient-rich zones suitable for plant growth and areas where nutrients are limiting. By combining these eight indicators during the creation of the adj-WSDI and its normalization, the average value was found to be ~ 0.53, with a maximum value of 0.99 (for highly degraded area) and minimum of 0.0 (for intact areas). Regarding the location in the landscape, the centers of the wetland areas are mainly 5.23 km from the primary market, 3.3 km from other human-related landscapes such as village houses, schools, and churches, 2.21 km from the main road, and 2.48 from the main river.

Regarding the normality, the four variables related to the physico-chemical soil quality of wetlands did not follow a normal distribution. This was observed for structural quality (SSSI: $W = 0.261, p < 0.001$), soil susceptibility of erosion (eMCR: $W = 0.98, p = 0.004$), the critical value of OM (eMCR: $W = 0.226, p < 0.001$), and the degradation variable (adj-WSDI: $W = 0.984, p = 0.005$). Therefore, it was necessary to transform all these variables for subsequent analysis.

3.2. Correlation between indicators

We then analyzed the correlation between the variables to identify the relationship among them. Given the type of variables used (all indices on a scale ranging from 0 to 1, not normally distributed,

Table 2
Summary of variables used for wetland degradation indicators.

Description	DTM	DTH	EDR	DTR	SSSI	CSOM	eMCR	TransSDI	*Adj-WSDI*
Mean	5.23	3.32	2.48	2.21	15.43	30.69	0.46	0.35	***0.53***
Standard error	0.44	0.36	0.15	0.18	0.23	1.27	0.01	0.01	***0.02***
Median	3.29	4.67	2.61	1.31	15.53	20.13	0.45	0.32	***0.50***
Mode	1.53	2.38	0.21	0.18	16.81	20.97	0.55	0.51	***0.72***
Standard deviation	3.11	2.75	2.39	2.96	3.72	20.48	0.09	0.18	***0.43***
Sample variance	50.62	33.07	5.69	8.74	13.86	419.50	0.01	0.03	***0.11***
Kurtosis	2.56	3.49	2.51	11.49	−0.42	−0.48	0.89	0.89	***−1.53***
Skewness	1.78	1.86	1.18	3.18	0.15	1.03	0.71	0.71	***0.04***
Min	0.01	0.77	0.00	0.00	8.53	10.59	0.30	0.00	***0.00***
Max	8.69	7.12	5.55	6.65	27.25	88.16	0.77	0.98	***0.99***

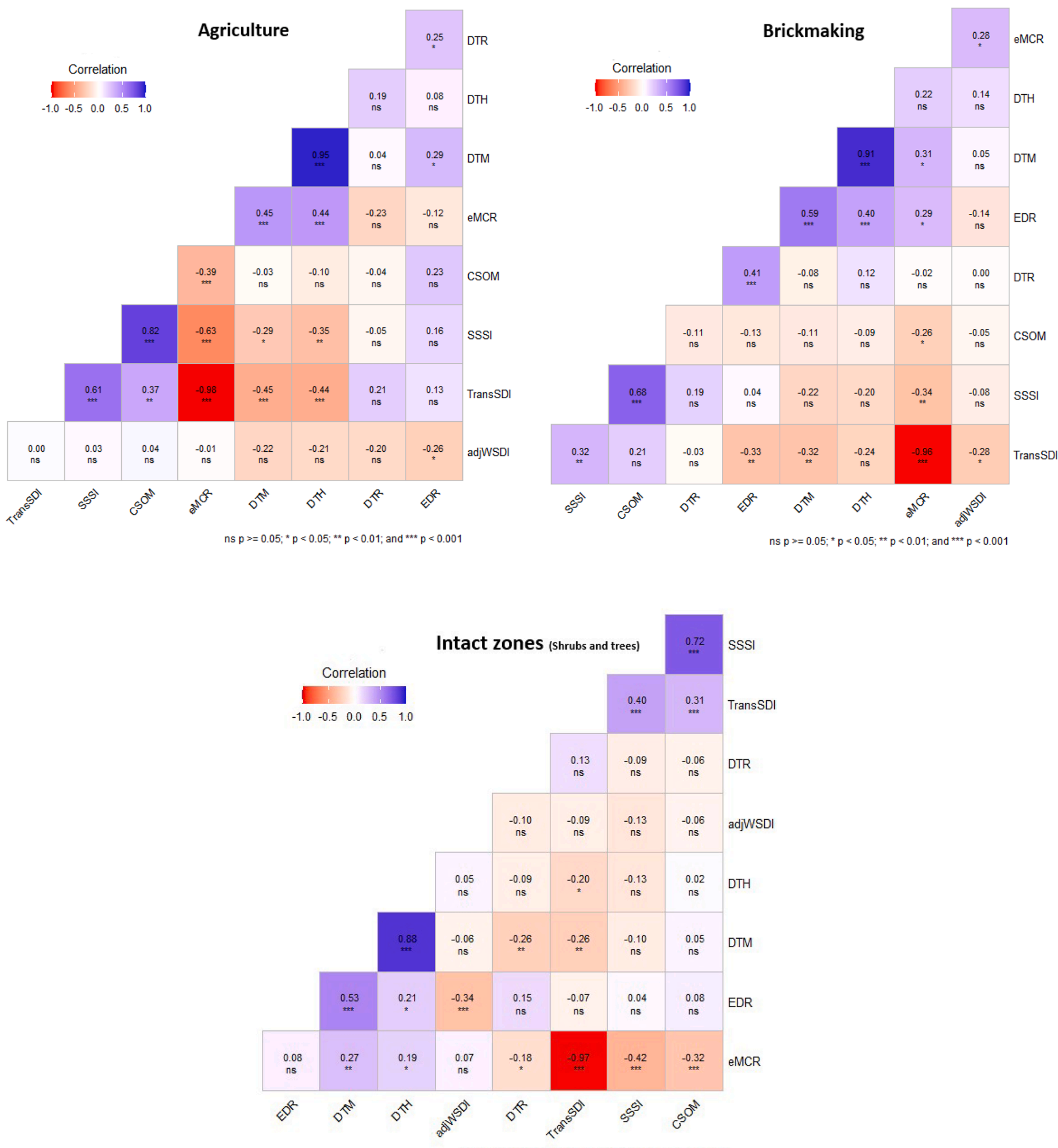

Fig. 3. Correlation between variables indicators for the three main land uses observed in wetland of eastern DR Congo.

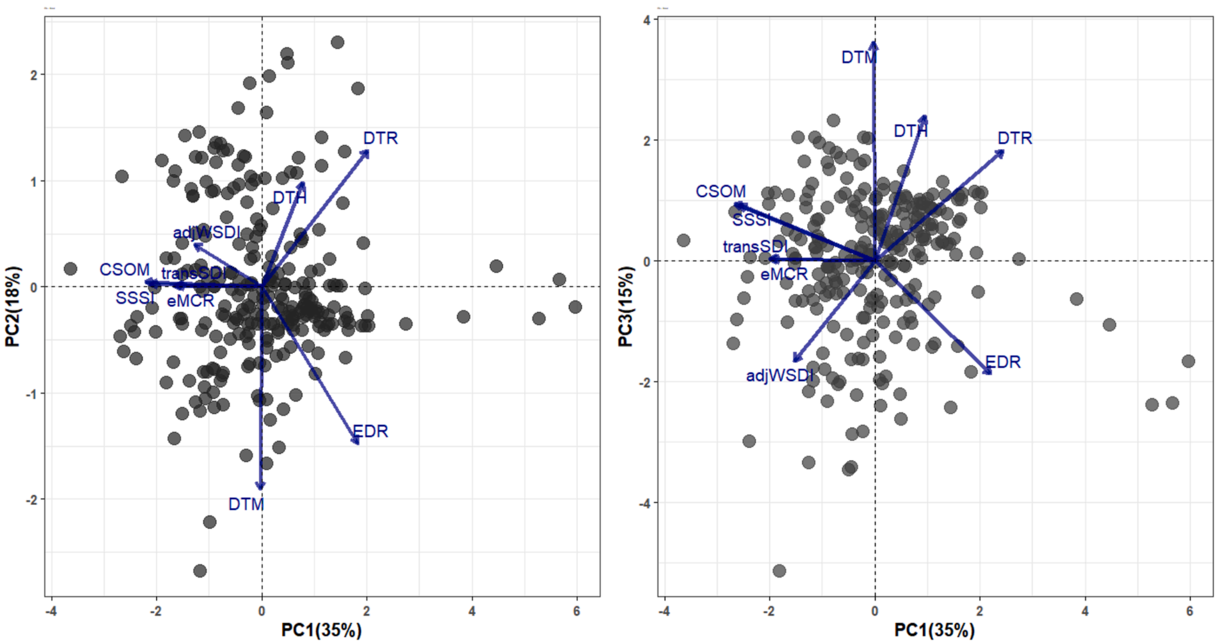

Fig. 4. Principal Component Analysis (PCA) between the factors used to access wetland degradation in South-Kivu, eastern DR Congo.

sometimes the relation between variables is not linear) and the robustness of the test, Spearman's correlation was applied to capture the maximum amount of information. The results of the Spearman's correlation were made for the three land uses selected in this study, as shown in Fig. 3.

For agricultural zones, the adj-WDSI was significantly correlated with the distance from the road ($r = -0.26$*) which, in turn, was positively correlated with the DTM (r = 0.29*) and the distance to the main river ($r = 0.25$*). The SSSI was highly significantly correlated with the nutrient availability index TranSDI($r = 0.61$***), the CSOM ($r = 0.82$***), but negatively correlated with eMCR ($r = -0.63$***), DTM($r = -0.35$**). Conversely, in brickmaking zones, adj-WSDI was positively correlated with eMCR (r = 0.28*) and negatively correlated with TrasnsSDI ($r = -0.28$*). SSSI was positively and significantly correlated with CSOM ($r = 0.68$*) and negatively with eMCR($r = -0.34$**) in these zones. Finally, in intact areas where no anthropogenic activities were reported, adj-WSDI was only significantly and negatively correlated with EDR ($r = -0.34$***), while eMCR was correlated with DTM ($r = 0.27$**) and DTH ($r = 0.19$*). TransSDI was highly significantly and positively correlated with SSSI ($r = 0.40$***), CSOM ($r = 0.31$***), and negatively with DTH ($r = -0.20$*), DTM ($r = -0.26$**), and eMCR ($r = -0.97$***). Although the effects were not significant, negative correlations were observed for agricultural areas between adj-WSDI and DTR ($r = -0.20$ *ns*), DTH ($r = -0.21$ *ns*), and DTM ($r = -0.22$ *ns*). Similarly, in intact areas, negative correlations were observed between adj-WSDI with DTM ($r = -0.06$ *ns*) and DTH ($r = -0.05$ *ns*) (Fig. 3).

Fig. 4 presents the results of the PCA conducted on the indicators. It also enabled the selection of variables to be integrated into the final indicator calculation using the MDS approach. Based on the eigenvalues, five dimensions were retained (see **Table S2**). Fig. 4 displays only the first three components, accounting for 68 % of the explained variance, while the five PCs explained 89 %. A commonality of 0.3 was considered acceptable between indicators and PCs. PC1 (34 % of variance) shows a positive loading value with DTR (0.597) and negative values for SSSI (−0.91) and EDR (−0.597). For PC2 (18 % of variance), only CSOM (−0.911) and eMCR (0.414) displayed significant values. Three indicators had high loading values for PC3: DTH (−0.912), DTR (−0.421), and TransSDI (−0.878). PC4 exhibited values for DTM (0.87), EDR (0.363), and DTR (−0.3), while PC5 showed values for eMCR (0.402) and TransSDI (0.884). After normalization and inclusion of the adj-WSDI, correlations were observed between adj-WSDI and soil quality indicators such as CSOM, SSSI, and TransSDI, as well as human-related landscape factors, including DTH and DTR. These correlations will need to be analyzed in the next section.

3.3. Level of degradation in different land uses, distance class, and drainage systems on the wetland degradation

The statistical distribution of the values of the indicator created (adj-WSDI) and its variation based on three factors are presented (**S** Fig. 1 and Fig. 5). The boxplot reveals that the degradation level in the two wetlands is 0.53 classified as moderate to severe degradation. Half of the collected points have a degradation level of 0.498 (moderate to severe), while 75 % of these points reach 0.82 highlighting that they are highly or extremely degraded.

The Kruskal-Wallis test shows that the degradation level varied significantly according to the three wetland types of use (H: *31.04, df: 2,* $p < 0.001$). A similar trend is observed for the drainage system applied (H: *40.12, df: 2,* $p = 0.004$) and distance from the wetland center (H: *209.9, df: 3,* $p < 0.001$). Agricultural areas exhibited an estimated degradation level of 0.52 (moderate), while brickmaking zones reached 0.62 (severe), and intact zones without anthropogenic activities had a level of 0.28 (Fig. 5a). Concerning drained and non-drained plots, we observe that completely drained areas exhibited a degradation level of 0.72 (extreme) compared to partially drained areas (0.48), while the intact zone maintained a level of 0.28 (Fig. 5b).

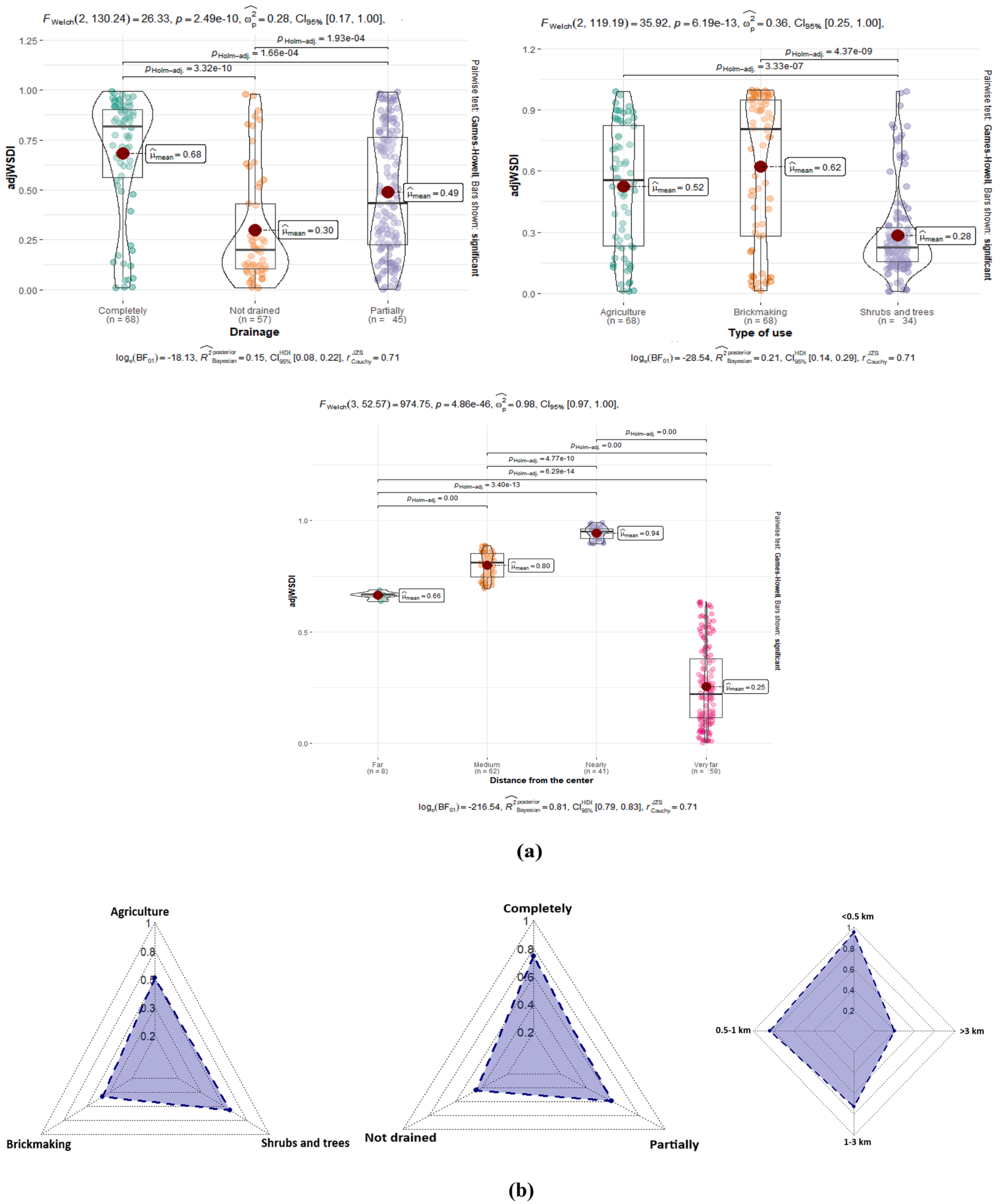

Fig. 5. The mean effect of adjusted-wetland soil degradation index (adj-WSDI) between land use types, distance class from the wetland center, and the drainage system. The first image (a) show the statistical distribution using boxplot while (b) show radar or spider chart.

3.4. Drainage and land use effects on wetland degradation

To assess drainage's effect on wetland degradation through the adj-WSDI, we analyzed the correlations between degradation levels and indicators, using the drainage system as a factor (Fig. 6a). The analysis revealed that SSSI and CSOM were positively correlated with degradation in completely drained areas, while it increased significantly with TransSDI but increased significantly with eMCR. For intact zone areas, a quadratic trend was observed for the level of degradation with a minimum of ~ 0.24 for a SSSI of ~ 20 and a peak of ~ 0.4 for an eMCR of about 0.45.

Analyzing the same results across different land use types, it was found that no correlation was observed between the level of degradation, eMCR, and TransSDI in agricultural zones. However, an increase was noted for SSSI and CSOM. In brickmaking zones, degradation remained positively and significantly correlated with eMCR and CSOM, while it decreased with SSSI and TransSDI. In intact zones, degradation was slightly correlated with eMCR but showed a strong and significant negative correlation with SSSI and TransSDI. No relationship was found between CSOM and degradation levels in intact zones.

3.5. Human-related landscape in and around wetland

Finally, we analyzed the degradation level across the entire landscape in and around the wetlands (Fig. 7). The results showed that points near the center (<500 m) and at a medium distance (0.5–1 km) from the wetland center were more degraded than those further away. In areas around the wetlands center, degradation remained high but showed no relationship with CSOM or SSSI. Beyond 1 km from the wetland center, degradation levels increased with CSOM and SSSI and appeared to stabilize at a certain threshold (generally around 0.50). TransSDI continued to increase significantly in these areas, while degradation decreased with eMCR. In all these cases, the average degradation level remained below 0.50. No relationship was found between degradation and eMCR or TransSDI for points very far from the center. However, a significant reduction in degradation was observed with an increase in CSOM and SSSI in these zones.Fig. 8.

3.6. Correlation between wetland degradation and human-related landscape

Simple linear models were conducted between the degradation level and the distance from the main river, road, market, and other human-related features such as villages, churches, and schools to analyze the relationship between wetland degradation levels and certain human-related landscapes. The results showed no significant relationship between degradation level and DT to market (R^2: 0.031, $p = 0.955$ *ns*). However, negative relationship was found with the distance to the main river (R^2:*0.08*, $p = 0.092$ *ns*) and, more prominently, with the DT to the main road (R^2:0.611, $p < 0.01$***). Additionally, the distance to human-related landscapes, mainly villages, school or church significantly and negatively affected degradation (R^2:*0.52*, $p < 0.001$***). Therefore, the closer a wetland is to roads and human-related landscapes, mainly villages, the higher its degradation level appears to be. Furthermore, to analyze whether the degradation is clustered, randomly distributed or dispered in space, the Moran's I was calculated. The Moran's I results

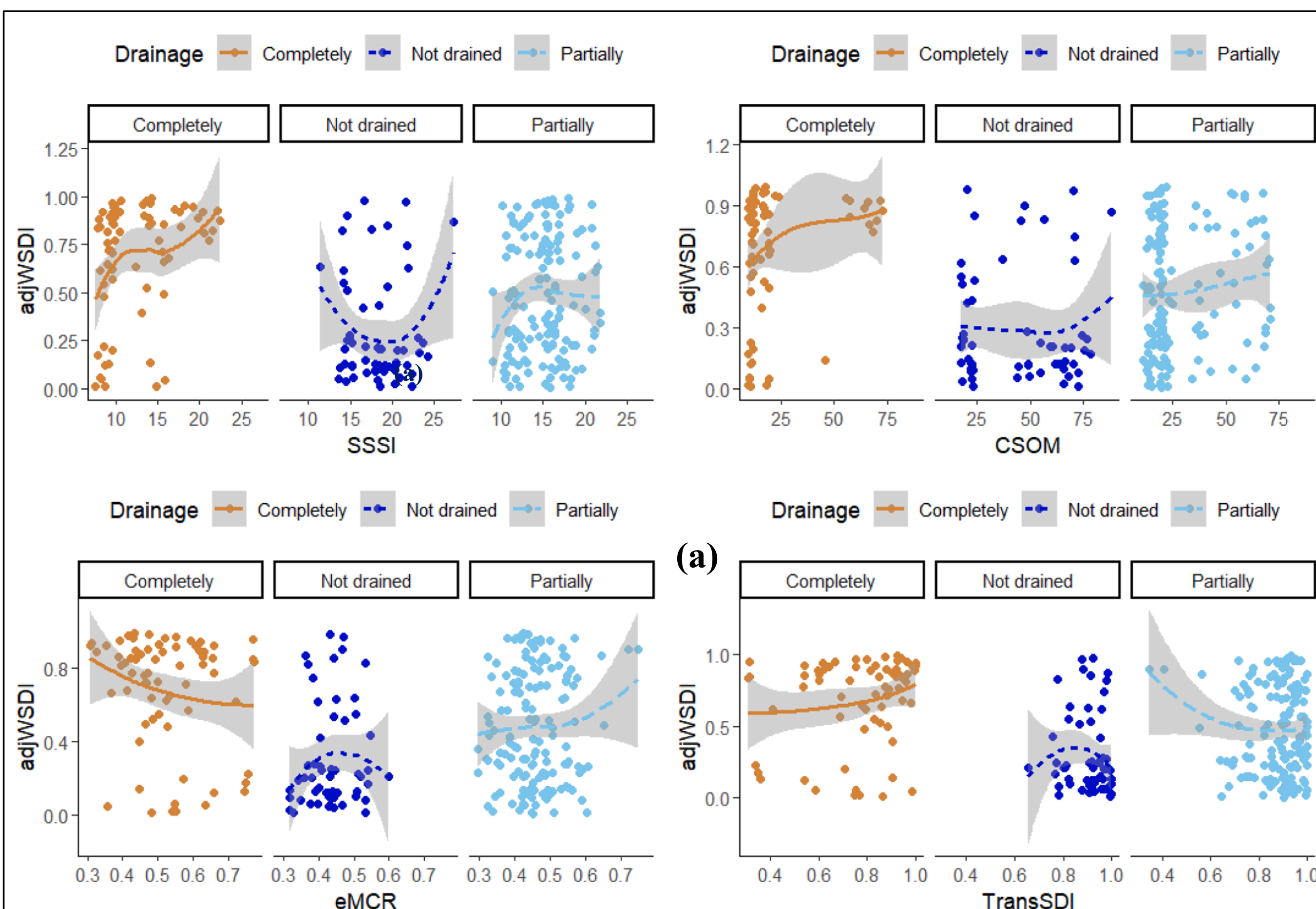

Fig. 6. Predicted wetland soil degradation (adj-WSDI) as a function of soil quality indicators in the three drainage systems (a) and in the three land uses (b) observed in wetlands in South-Kivu, eastern D.R. Congo.

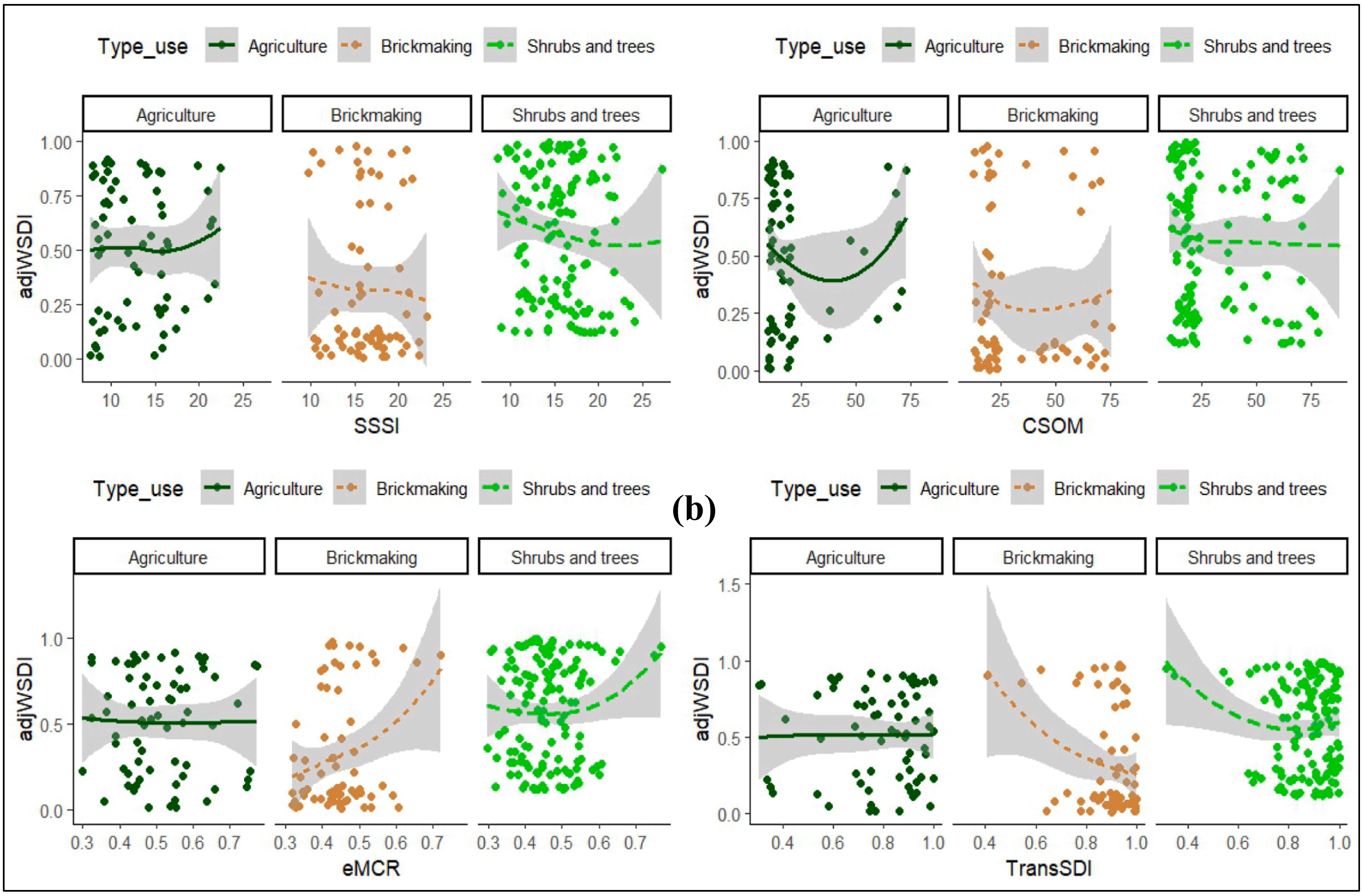

Fig. 6. (*continued*).

attest that in the two sites there is a less than 1 % and 5 % likelihood that the clustered patterns could be the result of random chance (Moran's Index: 0.604 and 0.226, Z-Score: 3.36($p < 0.001$***) and 2.07 ($p = 0.038$*)). This result highlights areas where the effects of human land use are concentrated and spatially structured, as well as others with weaker spatial clustering, indicating ongoing landscape transitions.

4. Discussion

4.1. Extended indicators for wetland degradation assessment

We found that the two wetlands had average SSSI, CSOM, eMCR, and TransSDI values of 15.4, 30.6, 0.46, and 0.35, respectively. However, these values varied depending on land use type, the drainage system availability, and the distance from the wetland center. SSSI showed low values ranging from 4 to 10 in completely drained areas, including a high risk of structural instability (Awoonor et al., 2024). Values below 5 indicated severe degradation. These low values were observed in some agricultural and brickmaking areas where pronounced drainage was present, and sometimes in places with small roads or vehicle access paths.

Regarding CSOM and eMCR, they ranged from moderate (0.75–1.5) to old soils (<0.75) and from structural loss (CSOM < 5) to more stable soils (CSOM $\geq$ 9). This structural loss was mainly observed in brickmaking areas compared to agricultural zones, and even less in intact areas. This can be explained by removing the surface soil layer and exporting clay-rich soil layers during brick production. As for TransSDI, which is related to fertility, it ranged from moderate to low, moderate fertility levels were observed in intact and agricultural zones (Mujiyo et al., 2022; Awoonor et al., 2024; Laribi et al., 2024). Fertility was slightly higher in agricultural areas due to the application of fertilizers, organic matter, and biomass restoration during harvest compared to brickmaking areas, where everything is burned, and fertile horizons are stripped. However, it is important to note that these soil physical quality indicators often provide only qualitative information. The degradation level will depend on thresholds set in the literature, which are not specific to a particular wetland type or land use.

4.2. Human-related landscape and wetland degradation

This study also demonstrates that wetland degradation is not solely a matter of soil physical and chemical quality. It is also linked to human activities and landscape modifications within and around these areas. Changes in the landscape from the wetland center outward further confirm this observation (Mack, 2006; Matthews et al., 2009; Ripl, 2010; Hong et al., 2017). We found a significant link between human-related landscapes and the degradation of wetlands. Given the primary uses of wetlands, particularly agriculture and brickmaking, areas more accessible by vehicles or people working as laborers tend to experience higher levels of degradation. Brick production only occurs in wetlands where vehicles can transport bricks from the production site to urban areas. Wetland areas, even those rich in clay and desirable for such activities, are difficult to exploit if they are not accessible, as this raises cots for both producers and buyers. Risks such as breakage and increased prices due to high transportation costs have also been noted. A similar trend is observed for areas where agricultural activities take place. The more accessible a wetland is by road, the easier it is to export produce to urban markets and access agricultural inputs, which promotes agricultural development. Road accessibility generally increases unregulated resource extraction. Additionally, roads can disrupt the natural hydrology of wetlands by acting as barriers to water flow (Leibowitz, 2003; Leibowitz et al., 2018). Wetlands near village houses showed higher

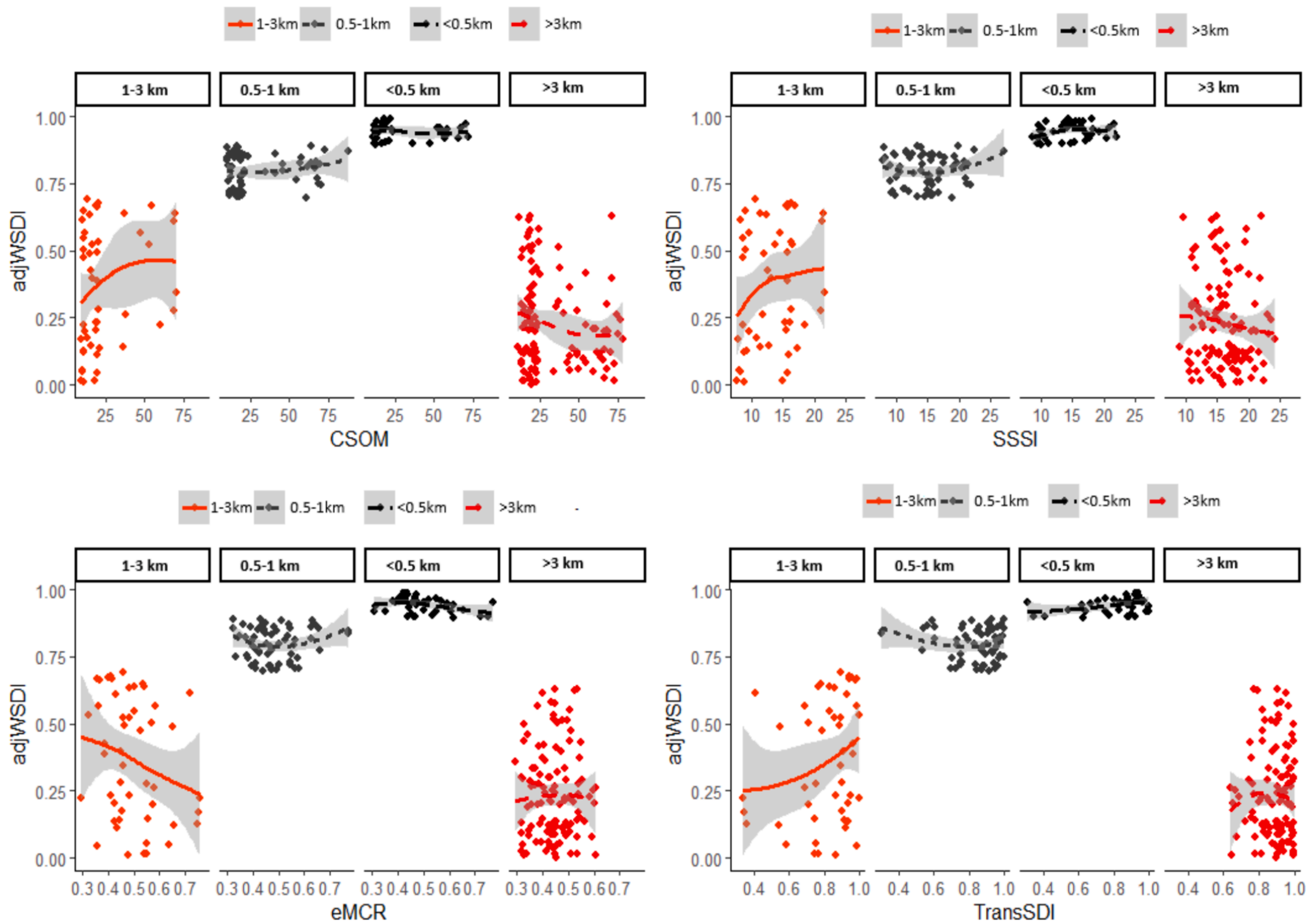

Fig. 7. Predicted wetland soil degradation as a function of soil quality function (SSSI, CSOM, eMCR, and TransSDI) the distance are circle concentric from the center to the outlet of wetland (the circle concentric were grouped in four classes with a 500 m radius from the wetland center outward into: "central": ≤0.5 km, "medium closer":0.5–1 km, "far"::1–3 km, and "very far": ≥3km.

levels of degradation compared to those further away. This is mainly due to due to two factors: firstly, the availability of a readily accessible workforce for activities; and secondly, the significant pressure from waste disposal. Wetlands have long been neglected and often served as dumping sites for various types of waste, contributing to their degradation. Numerous studies have highlighted the role of human activities in accelerating their degradation. The development of residential areas also leads to habitat loss for wetland species (Chuma et al., 2022; Kundu et al., 2024). If this urban development continues, it may eventually create heat islands around and within wetlands, potentially altering wetland microclimates, affecting species composition, and disrupting ecosystem dynamics (Moomaw et al., 2018; Pandey & Ghosh, 2023).

Brick production contributes to soil compaction through the creation of small trails. The impact of brickmaking on the decline of SOM is due to the removal of the topsoil, which is essential for agriculture, and the long-term use of deeper soil horizons that are poor in SOM. In peatland, for example, the peat layer is stripped and exposed to air, increasing pollution and GHG emissions, which drastically reduce SOM levels. Additionally, vegetation biomass is often cut and used to cover bricks or as fuel for brick firing. The removal of surface soil results in very poor layers in essential nutrients for plant growth (P, N, C, etc.), leading to soil destabilization and increased erosion through the formation of rills. Brick firing releases through ashes some bases to the surface, but they are often insufficient and mostly washed away with runoff. At the same time, the smoke and waste by-products from brick kilns further contribute to air and soil pollution (Guttikunda et al., 2013; Charvet et al., 2022; Getahun et al., 2024).

According to drainage, many studies have already demonstrated the impact of drainage on wetland degradation (Walters & Shrubsole, 2003; Blann et al., 2009; Huu Nguyen et al., 2016; Mitchell et al., 2022). To gain space for agricultural activities, farmers (or agricultural rural cooperatives) engage in drainage, which is often poorly executed and leads to the drying up of wetlands. Drainage thus results from the rapid lowering of the water table and its associated effects on wetland functioning. Human-related landscapes significantly influence wetland degradation by altering their ecological integrity and reducing the capacity to provide essential services. These researches also revealed that the application of drainage leads to changes in the groundwater table and the direction of infiltration, subsequently causing water loss from the aquifer. Large and deep drains are responsible for more remarkable hydrological alteration in wetlands (Blann et al., 2009; Mitchell et al., 2022). Therefore, to prevent the resulting ecological degradation, blocking some drains is a viable option to avoid changes in the hydrological factor. This constitutes the primary measure for any ecological restoration of wetlands.

To achieve sustainable management, recommendations must be made to establish buffer zones between wetlands and human-related landscapes, promote sustainable agricultural practices that minimize soil degradation, and implement restoration intervention plans to rehabilitate already degraded areas. It is essential to encourage local communities, support their engagement, and promote conservation ideas while making policy recommendations to decision-makers. This

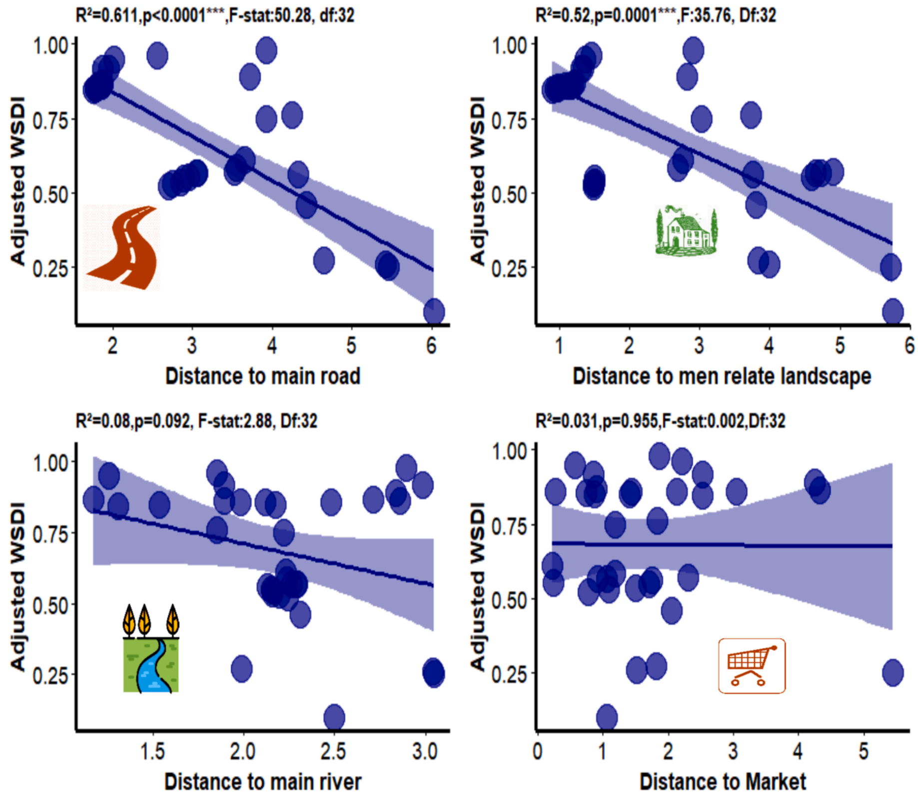

Fig. 8. Prediction of the relationship between wetland soil degradation and human-related factors in South-Kivu province, eastern D.R. Congo.

implies that the interaction between human-related landscapes and degradation must be well-integrated into a holistic management approach. Such an approach would not only focus on the ecological restoration of wetlands but also consider the needs of surrounding local populations, the impacts on nearby infrastructure, water quality, biodiversity, and existing conservation policies (Brouwer et al., 2003; Turner et al., 2003; Wood et al., 2013). The results of the Moran's I test indicate a similar trend for both areas: the distribution of WSDI classes is not random but spatially structured. This test revealed that similar values (high or low) of WSDI are spatially clustered or dispersed. Both indices being positive confirm the presence of positive spatial autocorrelation. The spatial structure appears to be slightly stronger in the first area than in the second (Fig. 9). Similar conclusion was observed by Zhu et al., (2022) and Chen et al., (2022). It is important to note, however, that two points deviated from this overall trend (see Fig. 9**: W1**). These points showed low WSDI values, indicating low degradation, despite being located within degraded areas. Several factors could explain this anomaly. One point corresponds to a sediment deposition zone from a nearby brick-making site, while the other is located near an abandoned aquaculture site, both of which have resulted in a slight slope, some vegetation cover (as confirmed by higher NDVI values), and higher sand content.

The results from the Moran's I confirm the existence of degradation hotspots, microhabitats or restoration potential, where the effects are strongly linked to human-related landscape, and that should be explored further. These are often located near roads, villages, brick-making sites, or areas of intensive agriculture. In the surrounding landscape, it indicates that degradation is spatially structured and correlated with these human activities, providing a strong basis for targeted management of sensitive zones. Whereas, in areas where the effects are significant but moderate (such as in Fig. 9**: W2**), landscape transitions are often observed, along with a diversity of land-use practices. This implies the need for fine-scale, micro-local approaches, such as assessments at the plot or brick production site level. In contrast, sites where the WSDI yields a Moran's I value close to zero may correspond to highly heterogeneous or rapidly transitioning landscapes. These might reflect overlapping human activities with opposing impacts (such as the coexistence of agriculture and brickmaking within the same parcel or adjacent areas). In such cases, it becomes difficult to intervene effectively without a detailed understanding of local dynamics. The spatial analysis from the Moran's I and all the above results help to conclude that the developed indicator can inform and guide both wetland management and land-use zoning by helping to prioritize degraded areas for ecological restoration and by supporting the designation of protective buffer zones. It can also serve as a monitoring tool to track changes over time. Furthermore, such an indicator functions as a policy benchmarking instrument for assessing the condition of wetlands. Overall, it can be integrated into adaptive management frameworks to enhance decision-making and sustainability planning.

4.3. Limit of the methodology

This exploratory study aimed to develop a wetland soil degradation indicator and test it to assess the impact of land use, drainage system, and human-altered landscapes. Various types of degradation can be observed, including those related to heavy metals, pesticides, and other chemicals. Unfortunately, not all components of degradation were considered; here, we focused exclusively on soil compaction, erosion susceptibility, and structural stability as physical aspects and nutrient depletion as chemical aspects. Although in the selected areas, mineral washing activities that cause pollution through the discharge of heavy metals such as mercury, or industrial discharges, were not reported at the sites, the created indicator still has a limitation as it does not take this type of pollution into account. This opens the door to future research in refining the indicator by integrating the heavy metals, and remains a promising direction for upcoming studies.

Lastly, several studies suggest a focus on biological degradation. Although we analyzed part of this by integrating the decline of SOM, a

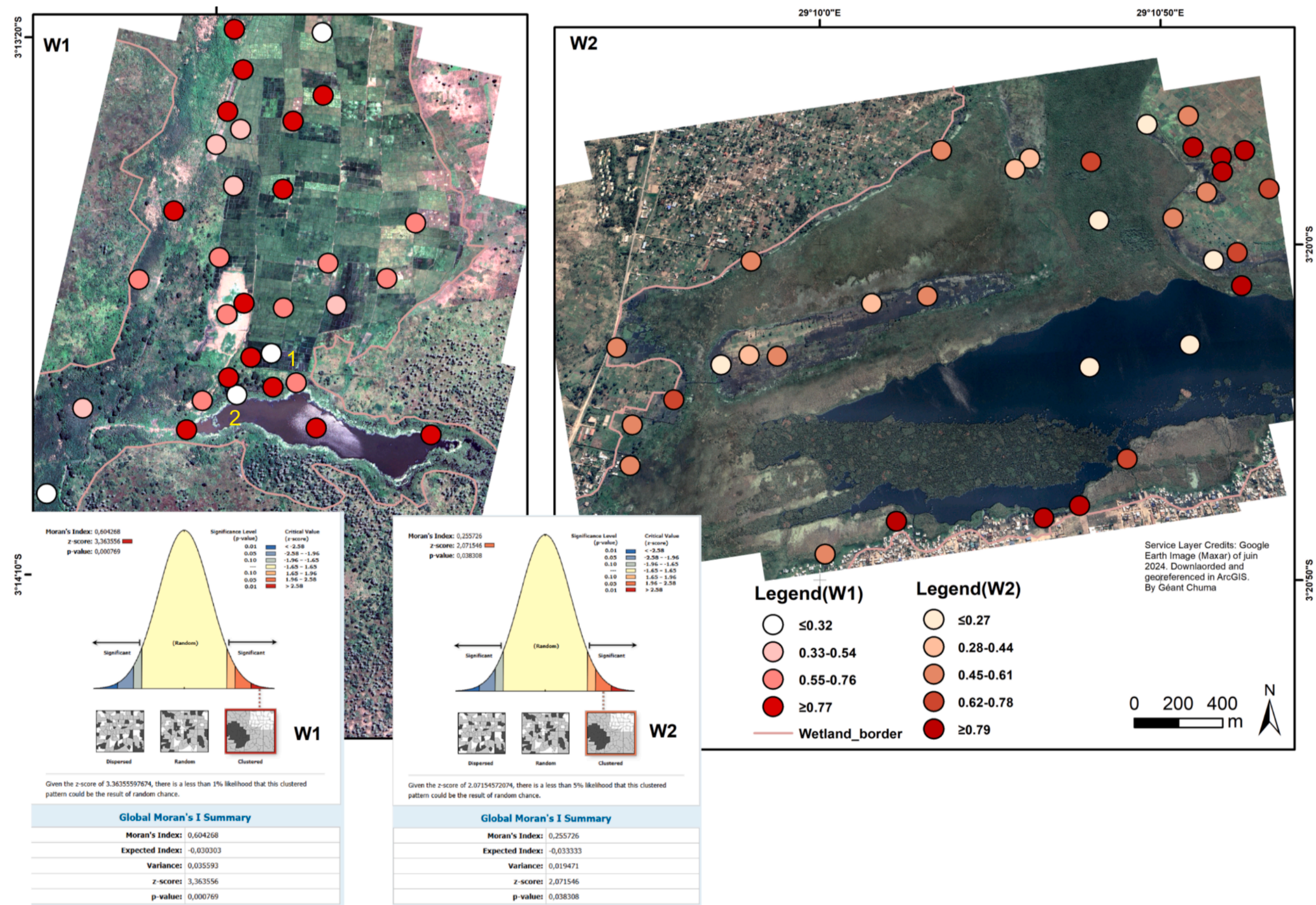

Fig. 9. Wetland soil degradation index in the two wetlands considered (W1 and W2). Here we use the Moran'I to assess the distribution of cluster created for the index (1 and 2 present the outlier).

significant aspect would involve the microbial activities decline, which could also impact nutrient availability and cycling (Sims et al., 2013; Howe et al., 2023; Cheng et al., 2024; Jiang et al., 2024). Given the cost and available resources, the study uses only two case studies, which limits the generality of the findings. Expanding the study to include more wetland types across diverse geographical regions would help test the universality of the degradation indicator developed. The study does not differentiate between wetland types (marshes, swamps, peatlands, etc), which could yield different degradation patterns. Wetland types vary greatly in terms of their ecological functions, and degradation indicators may need to be adjusted accordingly.

From a practical standpoint, we highlight that human-related landscapes (such as roads, villages, markets, etc.) are critical in shaping degradation; future studies could delve into specific agricultural practices that may contribute more directly to wetland soil degradation. As the negative effects of human activities may be amplified by climate change; understanding this interaction could therefore enhance our knowledge of wetland vulnerability. The added value of such an index primarily lies in its focus on elements essential to wetland functions, whether the areas are already degraded or under strong anthropogenic pressure.

Another key point is that commonly used remote sensing indices such as NDVI or NDWI (did not significantly contribute to the assessment of degradation and were excluded early on due to their weak explanatory power regarding wetland degradation. The proposed approach thus suggests starting with remote sensing as a broad screening tool, followed by more detailed soil data analysis

5. Conclusion

Wetland degradation seems to be a multifactorial phenomenon and often complex to be measured directly. However, modeling tools using multivariate techniques combined with biophysical properties provide valuable insights. The results indicate that the combination of seven indicators enabled the development of a wetland soil degradation index. Based on this index, degradation is primarily characterized by soil compaction and reduced porosity, loss of structural stability, and fertility decline due to the reduction of SOM and depletion of essential nutrients. Human-related landscapes significantly contribute to their degradation, particularly roads and village houses near wetlands. Certain activities, such as brick manufacturing, have an even more significant impact on these areas. These findings raise questions about the future of these wetlands in light of the increasing number of use and stakeholders. However, understanding and mitigating soil degradation is crucial for ecological integrity and maintenance of wetlands. This will help in sustaining the valuable service they provide. The added value of the developed Wetland Soil Degradation Index (WSDI) lies in its integration of elements that are essential for both conservation policies and land-use planning. Overall, WSDI can be seen as a powerful tool to guide evidence-based wetland zoning, prioritize restoration, monitor land-use impact, and inform both local management and policy decisions in areas under high anthropogenic pressure. For future research, further studies are needed to assess the trade-offs between economic activities such as brickmaking and the ecological functions of wetlands, particularly in areas vulnerable to climate change. Additionally, exploring how sustainable land-use practices can mitigate the impact of human activities on wetland soil degradation while maintaining ecosystem services should be a key focus.

CRediT authorship contribution statement

Chuma B. Géant: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mushagalusa N. Gustave:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Serge Schmitz:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2025.113987.

Data availability

Data will be made available on request.

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