THE RELATIONSHIP BETWEEN SOIL PHYSICOCHEMICAL PROPERTIES AND VEGETATION BIODIVERSITY IN NEWLY FORMED RESERVOIR BUFFER STRIPS

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Abstract. The patterns of soil physicochemical properties at large-scales such as buffer zone have been extensively studied, while at fine-scales of vegetation buffer strips (represent a trade-off between economic and ecology benefits of land) and the relationship with vegetation biodiversity are yet to be deepened. This study focused on the discrepancy between soil physicochemical properties (categorizing as soil properties, soil texture, soil stoichiometric ratio, soil microbial activity) and vegetation biodiversity indices in the buffer strips of newly constructed Chushandian reservoir, China. The results showed that the woodland buffer strips had higher soil microbial activity and carbon sequestration capacity than grassland and abandoned cropland. Soil physicochemical properties at 0 m in the reservoir buffer strips with three land use types were more influenced by the overlying water. Distance from watercourse is an important factor affecting soil properties in the reservoir buffer strips with different land use types, mainly mediated by affecting the vegetation biodiversity indices. The width of the existing grassland and abandoned cropland (20 m) is not enough for ecological restoration and should be appropriately widened. Finally, we suggest that the restoration of reservoir buffer strips should be set with flexible width according to the previous land use types.

Keywords: *ecotone, soil properties, soil stoichiometric, soil microbial activity, fine-scale*

Introduction

Buffer strips refers to the interface between aquatic ecosystem and terrestrial ecosystem, generally narrow-in-width, and play a disproportionately (to their surface area) important role in retaining nonpoint pollution, slowing surface runoff, resisting hydraulic erosion, and connecting landscapes (Hickey and Doran, 2004; Mander and Tournebize, 2015). Buffer strips are considered to be the last barrier against pollution from upland agricultural production, and their effectiveness is closely related to the species of vegetation attached to them, which is usually classified as wooded buffer strips, vegetation buffer strips, zone buffer strips (combined with woodland and grass) according to the configuration pattern of the vegetation (Cole et al., 2020). For example, grassland buffer strips are more effective than wooded buffers in improving surface roughness, slowing runoff, and increasing infiltration rates. Wooded buffer strips have

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obvious advantages over grass in terms of carbon sequestration potential and response to climate change (Hazlett et al., 2005; Cole et al., 2020).

Strips width and slope are the two major factors affecting the retention efficacy of buffer strips (Liu et al., 2008). Obviously, the wider the stirps width, the wider the corridor space for plant and animal habitat and the more ecological benefits can be fully exploited (Hickey and Doran, 2004). However, for agricultural landowners, although it is generally accepted that buffer strips of a certain width should be provided, the extent of the strip’s width is controversial from the viewpoint of economic value and production cost (Buckley et al., 2012). Therefore, the width of buffer strips setting is a trade-off between the ecology function benefit of buffers and economic cost of adjacent agricultural activities, and maximizing the economic effectiveness of the land simultaneous guarantee the retention of pollutants in the buffer strips has always been a major concern of scholars (Buckley et al., 2012; Cardinali et al., 2014; Cole et al., 2020). Zhang et al. (2010) suggested that a 30 m buffer strips (slope ≈ 10%) could remove 80% of the contaminants from upland. Liu et al. (2008) proposed that a 10 m width and a 9% slope vegetation buffer strips had the optimal sediment trapping capacity. In contrast, Valkama et al. (2019) argued through meta-analysis that the width of the buffer strips did not significantly affect the retention of nitrogen in surface runoff and groundwater. These differences in buffer strips width setting were mainly caused by the type of pollutant, vegetation placement pattern, the shelter objective (river, stream, ditch, etc.). Current studies conducted on buffer strips have focused on nutrient retention above 30 m in width, which is clearly beyond what is acceptable to land managers, and that fine-scale (1-20 m) buffer strips studied are urgently needed to provide more evidence for buffer strips management (Hickey and Doran, 2004).

Current study on buffer strips has mainly focused on strip width setting, physical placement of vegetation type, and nutrient retention efficiency (Lin et al., 2002; Noij et al., 2012; Shan et al., 2014; Pöppl and Aydin, 2019), while research on the dynamics of soil physicochemical properties and influencing factors in buffer strips is still lacking. Numerous evidence from large scales such as riparian buffer zone (>100 m) suggested that the hydraulic gradient induced by distance from river edge is the most direct factor driving the heterogeneity of riparian ecosystems (Xia et al., 2018). The distance from watercourse varies, with corresponding changes in vegetation diversity (Tsheboeng et al., 2017; Park and Kim, 2020; Zhao et al., 2020), soil aggregates (Ran et al., 2020; Liu et al., 2021) and physicochemical properties (Vidon et al., 2010; Stutter and Richards, 2012) in the riparian buffer zone. For example, both soil organic carbon and nitrogen showed an increase with distance from the watercourse (Xia et al., 2018). Soil texture near watercourse is characterized by coarse particles and low levels of organic matter (Dorioz et al., 2006). Thus, it is not known whether the buffer strips as a narrow area (<30 m) exhibits similar characteristic on the fine distance scale. However, it is certain that the buffer strips, as an interactive interface directly adjacent to the watercourse, has always been a hotspot for various soil geochemical processes and is influenced by abiotic factors both from the water and the upland (Vidon et al., 2010). In addition, the soil properties of the buffer strips are the result of a combination of chemical processes, environmental factors, vegetation types, and litter input and output. E.g., dissolved organic carbon (DOC), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) characterized the labile components of the soil nutrient pool with rapid turnover rate and are important indicator of soil microbial activity in the ecosystem (Dong et al., 2022; Zhang et al., 2022). Soil stoichiometric ratios can regulate nutrient cycling through microbial activity and mineralization rates (Lu et al., 2018; Yu et al., 2020). Likewise, soil texture has also been widely shown to exhibit a close relationship with the distribution of soil nutrients (Jiao et al., 2014; Zhao et al., 2020). Vegetation type modulates the content and ratio of soil nutrients mainly through the quantity and quality of above-ground litter input and belowground root excretion dynamics (Liu et al., 2021). Hence, the study of the relationship between soil physicochemical properties and vegetation biodiversity in buffer strips can help scientists better understanding the formation process and structural functions of soils and can provide references for studying ecology processes such as soil-plant relationship, spatial patterns of vegetation, soil erosion, and land use changes (Zhao et al., 2020).

The Huai River Basin is located in the eastern part of China between the Yangtze River and the Yellow River. The length of the main stream is 1050 km, and the basin area is 27×10^4 km^2. Chushandian Reservoir is the only large-type reservoir built in the upper reaches of the main stream of the Huai River. The reservoir is a large-scale water conservancy project constructed mainly for flood control, irrigation, water supply, and power generation. The stored water reached its baseline (normal) level for the first time in October 2020. The reservoir’s location is mainly based on the original channel of the Huai River, and the surrounding area of the original channel has been widened, nearly 40,000 residents have been relocated. The land use types around the reservoir in the early period were mainly cropland and commercial woodland (agroforestry management system). During the construction of the reservoir, some of the cropland was abandoned and gradually evolved into grassland (natural recovery), and some of the cropland was not abandoned for cultivation until the water level arised. Therefore, after reservoir impoundment, a mosaic landscape pattern dominated by abandoned cropland, grassland and commercial woodland was formed around the shoreline. Since the different land use types were previously operated by scattered farmers, the landscape was fragmented and the width of independent land use type was usually between 25-30 m, which was the basis for the next step of reservoir buffer strips construction. This provide good experimental conditions for studying soil physicochemical properties of buffer strips with different vegetation types.

We presumed that soil chemical processes in the buffer strips with different land use types had reached a steady state at the time of experimental sampling after two months of reservoir impoundment. This study focused on the soil physicochemical properties and vegetation biodiversity in the buffer strips with three land use types (abandoned cropland, grassland, and woodland) around watercourse after reservoir impoundment, aim to: 1. Comparing the differences of soil physicochemical properties between the reservoir buffer strips with three land use type. 2. Exploring the variation patterns of soil physicochemical properties in the buffer strips with three land use types at the fine distance scale (0-20 m). 3. Revealing the relationship between physicochemical properties and vegetation biodiversity and identifying the main factors influence soil properties in the reservoir buffer strips with three land use types. It is expected to contribute new insights to the understanding of the relationship between soil-plant in the buffer strips, and to provide a reference for the width setting and restoration of the reservoir buffer strips. The limitation of this study is that since unfortunately no background values of soil physicochemical properties were obtained before the dam was constructed, it is difficult to infer whether the differences between land use types are due to prolonged inundation.

Materials and Methods

Study Area

We carried out our experiment along the reservoir buffer strips of the Chushandian Reservoir (N32°22'-32°32', E113°89'-113°96') in Xinyang city, Henan Province, China. Xinyang is a transitional region from a subtropical climate zone to a warm temperate zone located in the southern part of Henan Province. The city is located at the dividing line of the Qinling and Huai Rivers. The terrain is high in the south and low in the north, with an altitude of 75-300 m. The annual average temperature is generally between 15.3-15.8°C, and the annual average rainfall is 993-1,294 mm. The air is moist and the relative humidity ranges from 74-78% annually (China Meteorological Data Sharing Service System, http://data.cma.gov.cn). There are many rivers in this region, which belongs to the Yangtze River catchment and the Huai River catchment, and the Huai River basin accounts for 98.2% of Xinyang city’s area. Due to the influence of Xinyang’s particular geography and climate, the spatial and temporal distribution of rainfall is uneven, and precipitation varies greatly within and between years. Xinyang’s precipitation mainly comes in June to August, and the difference in precipitation between wet and dry years can be a factor of up to 3. The main forest trees species in this area are *Pinus massoniana* Lamb, *Cunninghamia lanceolata* (Lamb.) Hook., *Pistacia chinensis* Bunge, and *Quercus dentata* Thunb., among many others. These tree species are distributed in pure forests or mosaics and form the main surrounding forest community (Hu et al., 2018).

Field Investigation

We conducted our soil survey on December 11, 2020, which was two months after the first controlled flood of the reservoir area reached its predetermined normal storage level. The local soil texture type was mainly ACRISOLS soil (based on the FAO World Reference Base) with heavy soil viscosity and weak acidity.

Along the western bank-line of the reservoir (without dike protection) we selected three land use types (abandoned cropland, grassland and woodland), and three plots of similar conditions were selected as replicates for each land-use types (9 in total) (*Figure 1*). The sampling strip distance was set according to the actual plot size of different land-use types along the watercourse of the reservoir. As the different historical land use types were previously operated by a patchwork of farmers, the landscape was fragmented, and the width of independent land use types ranged from 25 to 30 m. In order to eliminate the influence of boundary effects of adjacent sample plots, we set up sampling strips of 0 m, 2 m, 20 m within different land use types along the bank-line according to the distance from watercourse. For convenience of expression, we wrote land use types and distance scales together as woodland: W0, W2, W20; grassland: G0, G2, G20; abandoned cropland: C0, C2, C20. We collected 27 soil samples in total. More detail about the plot setting and location of sampling sites can see our pervious article (Yan et al., 2022).

Soil Sampling

Taking the boundary between watercourse and land as a sampling point of 0 m, we took our samples using a *Petersen* grab, and three adjacent soil samples were selected for each location and mixed into one. At 2 m and 20 m we collected 5 soil cores intact near the sampling point at 10 cm depth, mixed them into a homogeneous composite sample, and kept an additional soil core intact that was immediately brought back to the laboratory for measurement of soil bulk density (BD) and soil water content (SWC). We did not measure the physical properties of the soil at 0 m because the soil at this location is at the land-water interface and it was too difficult to collect a complete soil core intact. All composite samples were divided into two sections. One was kept in a self-sealed bag and placed in a refrigerator at 4° C for the determination of ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), DOC, MBC, and MBN content. And the other one was stored in a self-sealed bag and brought back to the laboratory for air drying. Stones and roots were picked out with forceps and separated into two portions using a 2 mm sieve. One portion was used to determine the soil particle structure, and the other was screened through a 0.25 mm sieve and refrigerated at 4° C for pH, soil total carbon (TC), total nitrogen (TN), total phosphorus (TP) determination. All tests were conducted within two weeks after sampling.

Figure 1. *Three land use types around the Chushandian reservoir's buffer strips*

Vegetation Survey

Strips transect (parallel to the stream direction) were set up at 2 m and 20 m in each sampling plot, and three 1 m × 1 m sub-sample squares were set up in each strips transect, with 10 m interval between squares. Vegetation survey was conducted in each square, and the species, number of each species, and coverage of all plants were recorded. Then, calculation of vegetation biodiversity indices (Simpson index, Richness index, Shannon index, Pielou index) for reservoir buffer strips with three land use types base on survey results. The vegetation biodiversity indices were calculated using the following formula (Liu et al., 2020).

Richness Diversity Index (S):

$$S = P_a \tag{Eq.1}$$

Simpson Diversity Index (*Simpson*):

$$Simpson = 1 - \sum (P_i)^2 \tag{Eq.2}$$

Shannon Diversity Index (*Shannon*):

$$Shannon = -\sum P_i \ln P_i \tag{Eq.3}$$

Pielou Diversity Index (J):

$$J = Shannon / \ln S \tag{Eq.4}$$

where P_a is the number of the species in the sample. $P_i = N_i/N$, N_i is the number of individuals of the ith species in the sample, N is the total number of individuals in the plots.

Laboratory Analysis

Soil Physicochemical Properties

We determined the level of TC and TN in our soil samples by elemental analyzer (Vario MAX C/N, Elementar Analysensysteme GmbH, Hanau, Germany), and soil pH was measured in distilled water mixed 2.5:1 (by volume) with dry soil by a Delta 320 pH meter (Mettler-Toledo Instruments (Shanghai) Ltd., China). We determined soil TP content by using the molybdenum-blue colorimetry method after digesting the samples with perchloric acid. Both NH_4-N and NO_3-N were extracted using 1 mol/L KCl, using a soil: KCl ratio of 1:10 and were both measured using an Automatic Discontinuous Chemical Analyzer (Smarthem200, Alliance Company, French). We extracted DOC with K_2SO_4 and determined its level by dichromate digestion. MBC and MBN were measured by the fumigation extraction method (Brookes et al., 1985; Wang et al., 2018), and we measured BD using the oven-drying volumetric ring method after samples were oven-dried at 105° C for 24 hours to a constant mass. We then calculated BD as the ratio of oven-dried undisturbed core weight to the cutting ring volume. SWC was determined by oven-drying the samples at 105° C for 24 hours, and the water content was expressed as a percentage of the dry weight. Soil particle-size is mechanically separated using the wet sieving method, detail see previous article (Yan et al., 2022).

Statistical Analysis

To reveal more comprehensively the relationship between soil physicochemical properties, all soil parameters obtained were classified into soil properties (include pH, TC, TN, TP, NH_4-N, NO_3-N), soil texture (include sand content, silt content, clay content), soil stoichiometric ratio (include C/N, MBC/MBN), and microbial activity (include MBC, MBN, DOC) before performing data analysis. We performed an analysis of variance (*ANOVA*), and post-hoc multiple comparison (*Tukey*) tests at the probability levels (p) of 0.05 to determine differences between the soil physicochemical properties and vegetation biodiversity indices in reservoir buffer stirps with different land use types. Two-way *ANOVA* was performed to determine the interaction between land use types and the distance from watercourse. *Pearson*'s correlation coefficient was used to analyze the relationship between soil properties at significance levels of 0.05 and 0.01. Mantel test was used to calculate the relationship between soil texture, soil stoichiometric ratio, microbial activity, vegetation biodiversity indices and soil property parameters with *LinkET* R package (Huang, 2021). In addition, we used principal component analysis (PCA) to explore the relationship between different soil parameters and vegetation biodiversity indices in reservoir buffer strips with three land use types and distances from watercourse. Redundancy analysis (RDA) was used to explore the main factors affect soil properties. Specifically, the variables with significant effects on soil properties were first identified using a combination of forward and backward selection, and then the explanatory rate as well as significance was calculated for the screened variables using the *rdacca.hp* package (Lai et al., 2022). Structural equation models (SEM) between land use types, distance from watercourse, soil texture, soil properties, soil stoichiometric ratio, soil microbial activity and vegetation biodiversity indices were constructed using a partial least squares path model (PLS-PM) with *plsm* R package. Barplots and residuals were constructed to check the common assumptions of homogeneity of variances, normality for all models, and lack of collinearity for multiple regression models, and variables were log10 transformed if necessary. All analysis was computed using R version 4.0.3. The main related packages used are *ggplot2*, *vegan*, *tidyverse* etc.

Results

Soil Physicochemical Properties in Reservoir Buffer Strips with Three Land Use Types

The reservoir buffer strips with three land use types were weakly acidic, with pH values varied in the range of 5-6.5; The soil TC and TN at W2, which were 26.08 and 2.13 g/kg, respectively were significantly higher than those at other sites. Soil TC and TN were significantly higher in woodland while TP was significantly lower than the other two land use types (*Fig. 2*); The content of NH_4-N at W20, which was 23.20 mg/kg, was significant lower than C0 and G0, and the content of NO_3-N at W2 and W20, which were 5.58, 3.62 mg/kg, respectively, was significantly higher than the other sites (p<0.05), and the content of NO_3-N varied significantly between three land use types, showing woodland > abandoned cropland > grassland; Soil bulk density (BD) at W20, which was 1.03 g/cm^3, was significant lower than C2, and the BD and SWC of woodland were significantly lower than the other two land use types (*Fig. 2*).

The contents of microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) at W20, which were 418.89 and 35.99 mg/kg, respectively, were significantly higher than those at the other sites (p<0.05); The content of dissolved organic carbon (DOC) at W20, which was 23.38 mg/kg, was significantly higher than those at the other site (except for W2).the content of MBC, MBN, DOC were significantly higher in woodland than grassland (*Fig. 3*).

At 51.11%, sand content of woodland soil was higher than that of the other two land use types. However, the silt content of woodland soil was significantly lower than that of the other two land use types (p<0.05) at only 34.75% (*Fig. 4*). The clay content did not differ significantly among three land use types. The soil C/N of woodland was 10.82, which was significantly higher than the other two land use types. The soil MBC/MBN of the abandoned cropland was 8.96, which was significantly higher than that of grassland (*Fig. 5*). The vegetation biodiversity indices did not differ significantly in distance scale and among different land use types (*Fig. 6*).

According to the results of the two-way *ANOVA* (*Table 1*), we found that the physicochemical parameters of the reservoir buffer strips with three land use type were affected by land use types except for TP, NH_4-N, Clay content, and MBC/MBN. While MBC and MBN also received effects from both distance from watercourse (F=114.66, p<0.001; F=8.14, p=0.01) and interaction between them (F=92.64, p<0.001; F=7.19, p=0.004). NH_4-N and MBC/MBN were only affected by the distance from watercourse (F=6.15, p=0.021; F=9.44, p=0.006).

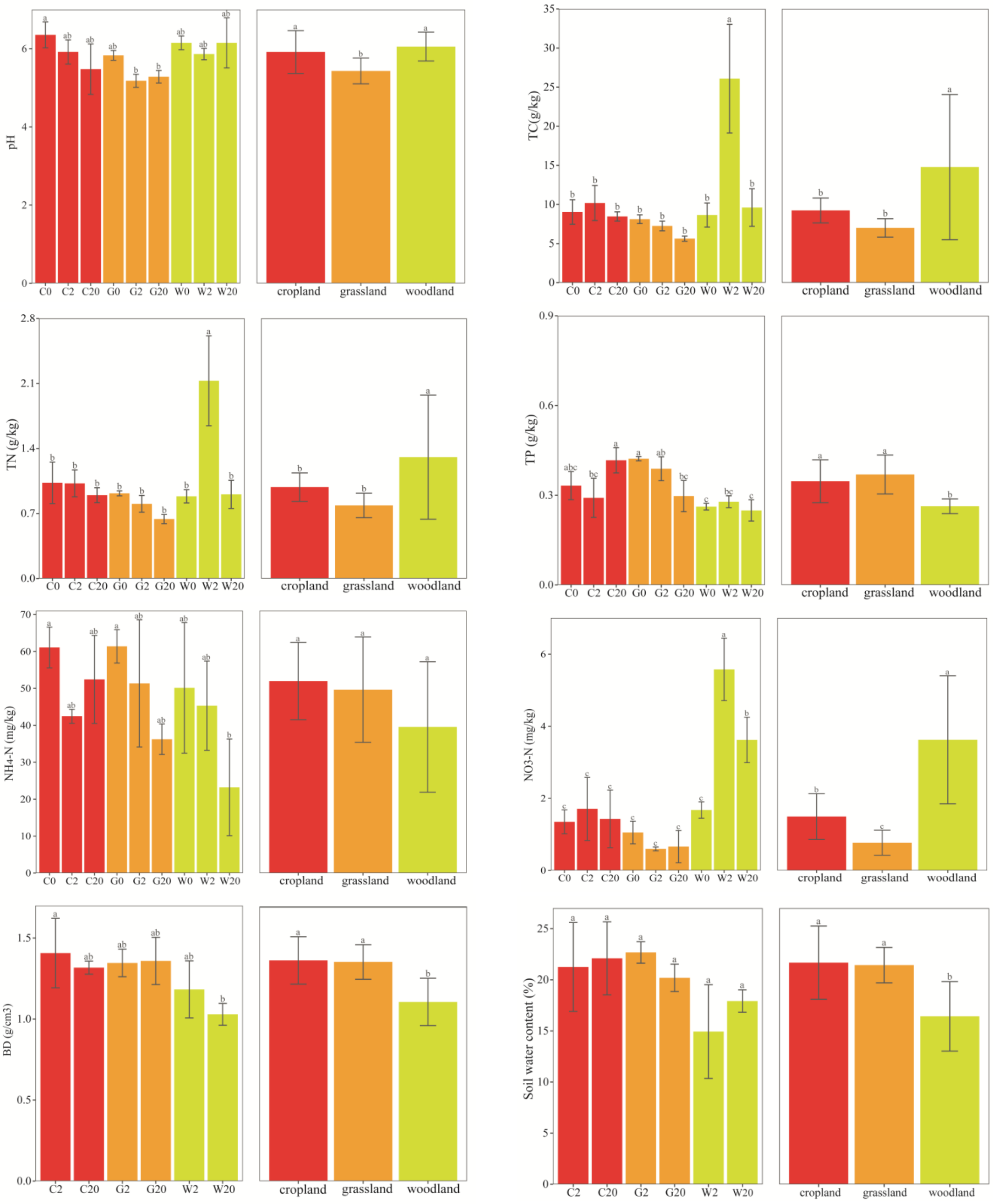

Figure 2. *Soil properties {pH, total carbon (TC), total nitrogen (TN), and total phosphorus (TP), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N), bulk density (BD), soil water content (SWC)}of reservoir buffer strips with three land use types. Left: Soil properties between different sites. Different lowercase letters indicate levels of statistical significance of soil properties between different sites ($p < 0.05$). Right: Soil properties between three land use types. Different lowercase letters indicate levels of statistical significance of soil properties between different land use types ($p < 0.05$). The vertical bars represent means, and the error bars represent standard errors*

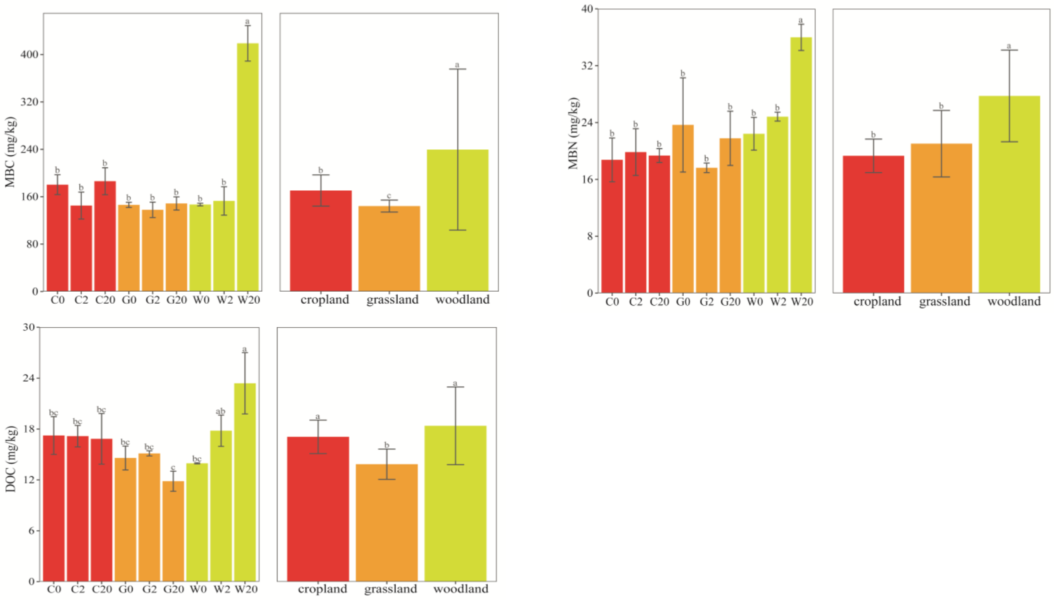

Figure 3. *Soil microbial activity {microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and dissolved organic carbon (DOC)}of reservoir buffer strips with different land use types. Left: Soil microbial activity between different sites. Different lowercase letters indicate levels of statistical significance of soil microbial activity between different sites (p < 0.05). Right: Soil microbial activity between different land use types. Different lowercase letters indicate levels of statistical significance of soil microbial activity between different land use types (p < 0.05). The vertical bars represent means, and the error bars represent standard errors*

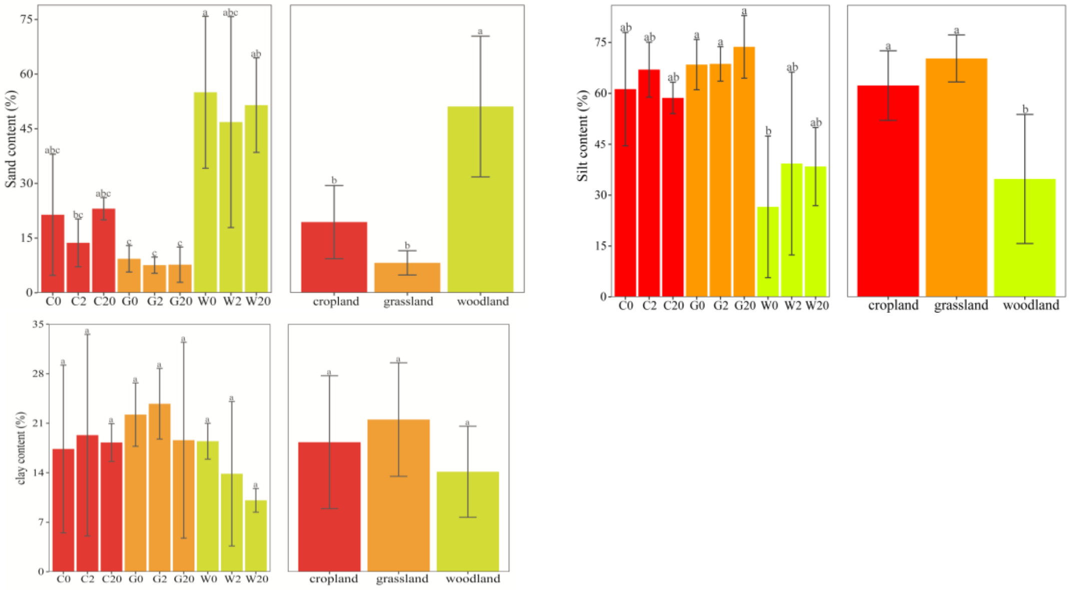

Figure 4. *Soil texture (Sand content, Silt content, Clay content) of reservoir buffer strips with different land use types. Left: Soil texture between different sites. Different lowercase letters indicate levels of statistical significance of soil texture between different sites (p < 0.05). Right: Soil texture between different land use types. Different lowercase letters indicate levels of statistical significance of soil texture between different land use types (p < 0.05). The vertical bars represent means, and the error bars represent standard errors*

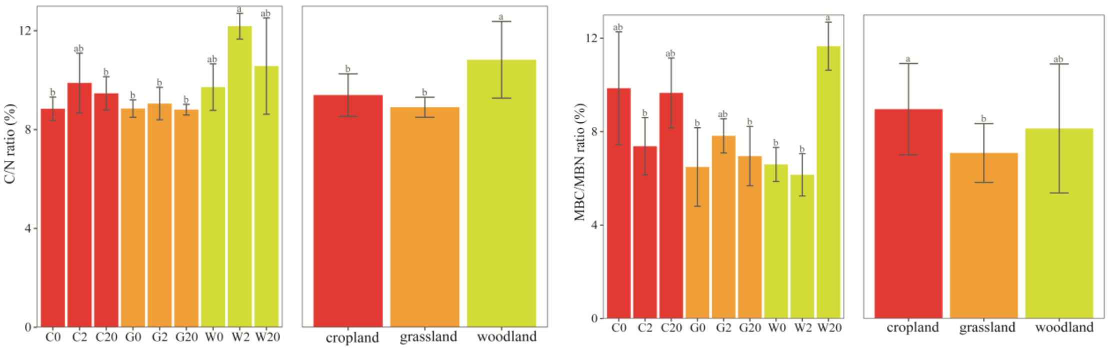

Figure 5. *Soil stoichiometric ratio{Soil carbon nitrogen ration (C/N), Soil microbial carbon nitrogen ratio (MBC/MBN)} of reservoir buffer strips with different land use types. Left: Soil stoichiometric ratio between different sites. Different lowercase letters indicate levels of statistical significance of soil stoichiometric ratio between different sites (p < 0.05). Right: Soil stoichiometric ratio between different land use types. Different lowercase letters indicate levels of statistical significance of soil stoichiometric ratio between different land use types (p < 0.05). The vertical bars represent means, and the error bars represent standard errors*

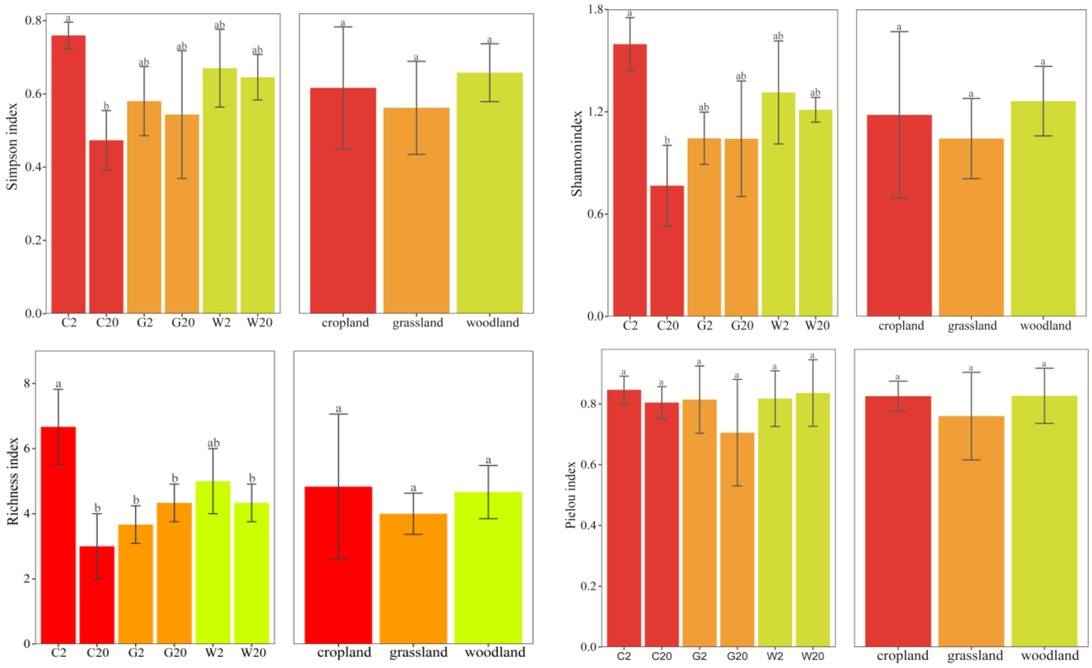

Figure 6. *Vegetation biodiversity indices (Simpson index, Shannon index, Pielou index, Richness index) of reservoir buffer strips with three land use types. Left: Vegetation biodiversity indices between different sites. Different lowercase letters indicate levels of statistical significance of Vegetation biodiversity indices between different sites (p < 0.05). Right: Vegetation biodiversity indices between different land use types. Different lowercase letters indicate levels of statistical significance of Vegetation biodiversity indices between different land use types (p < 0.05). The vertical bars represent means, and the error bars represent standard errors*

***Table 1.** The correlation and interaction of soil physicochemical properties between historical land-use types and distance from water (k=6, n=3)*

Soil properties	Historical Land-use types		Distance from water		Types × Distance	
	F value	P value	F value	P value	F value	P value
pH	3.66	0.028 *	2.60	0.121	-	-
TC	3.47	0.034 *	4.47	0.046 *	-	-
TN	4.12	0.018 *	3.02	0.096	-	-
TP	0.15	0.927	0.45	0.508	3.82	0.039 *
NH_4-N	0.70	0.564	6.15	0.021 *	-	-
NO_3-N	10.23	<0.001***	0.15	0.703	-	-
DOC	9.71	<0.001***	2.02	0.170	13.34	<0.001***
MBC	39.34	<0.001***	114.66	<0.001***	92.64	<0.001***
MBN	14.72	<0.001***	8.14	0.010 **	7.19	0.004 **
Sand	17.18	<0.001***	0.76	0.614	-	-
Silt	11.43	<0.001***	0.93	0.502	-	-
Clay	1.27	0.315	0.18	0.978	-	-
BD	7.26	0.007 **	1.54	0.235	-	-
SWC	5.41	0.018 *	0.09	0.764	-	-
C/N	5.77	0.005 **	0.09	0.762	-	-
MBC/MBN	2.80	0.086	9.44	0.006 **	7.46	0.004 **

pH (pH value); TC (total carbon); TN (total nitrogen); TP (total phosphorus); NH_4-N (ammonium nitrogen); NO_3-N (nitrate nitrogen); DOC (dissolved organic carbon); MBC (microbial biomass carbon); MBN (microbial biomass nitrogen); Sand (sand content); Silt (silt content); Clay (clay content); BD (bulk density); SWC (soil water content); C/N (carbon nitrogen ratio); MBC/MBN (microbial carbon nitrogen ratio); * indicates significance at the 0.05 level; ** indicates significance at the 0.01 level; and *** indicates significance at the 0.001 level. The variable k is the number of different sampling sites in each historical land-use type (not including 0m site due to lack of soil physical properties data), and n is the number of different historical land-use types

The Relationship Between Physicochemical Properties and Vegetation Biodiversity in Reservoir Buffer Strips with Three Land Use Types

Our analysis showed that TN was extremely positively correlated with TC (0.91, $p<0.01$), and both were positively correlated with NO_3-N and pH. pH was extremely positively correlated with NO_3-N and BD ($p<0.01$). TP was positive correlated with NO_3-N and negative with SWC ($p<0.05$). NH_4-N was positive correlated with BD and negative with SWC ($p<0.05$). Soil microbial activity was extremely correlate with NH_4-N, soil stochiometric ratio was extremely correlate with NO_3-N, and vegetation biodiversity indices was extremely correlated with BD and SWC (Mantel's $p<0.01$) (*Fig. 7*).

It can be seen from the PCA results that different sites of reservoir buffer strips with three land use types were well distinguished, 0m site of three land use types all clustered together and positive correlated with SWC and NH_4-N. The 2 m and 20 m site of woodland clustered together, and were positive correlated with TC, TN, sand content,

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soil microbial activity and stoichiometric ratio. The 2 m and 20 m site of grassland and abandoned cropland was not clearly distinguished on the first component axis, while were well separated on the second component axis. Grassland was positive correlated with Silt content, Clay content and TP, and abandoned cropland was positive correlated with vegetation biodiversity indices (*Fig. 8*).

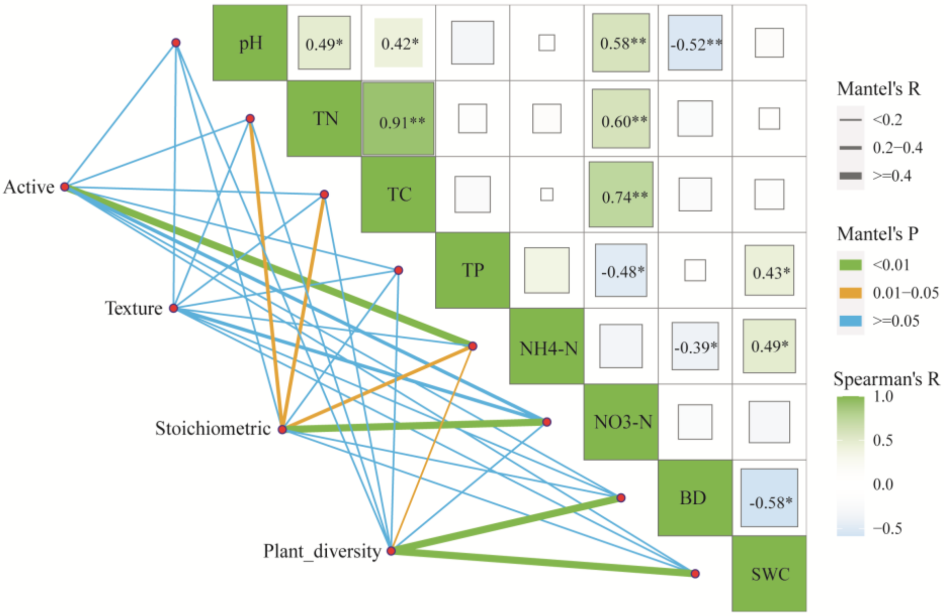

Figure 7. *Pairwise comparisons of soil properties are shown, with a color gradient denoting Spearman's correlation coefficients (* indicated significance at the 0.05 level; ** indicated significance at the 0.01 level). Microbial activity (Active), Soil texture (Texture), Soil stoichometric ratio (Stoichometric), and Vegetation biodiversity indices (Plant_diversity) was related with each soil property parameters by Mantel tests. Edge width corresponds to the Mantel's r statistic for the corresponding correlations, and edge color denotes the statistical significance based on 9,999 permutations. Abbreviation for soil properties: pH; TN (soil total nitrogen); TC (soil total carbon); TP (soil total phosphorus); NH4-N (ammonium nitrogen); NO_3-N (nitrate nitrogen); BD (soil bulk density); SWC (soil water content)*

The results of the RDA analysis showed that soil microbial activity, soil texture, soil stoichiometric ratio and vegetation biodiversity indices could explain 47.54% the variation of soil properties, with 38.7% in the first axis. Simpson index, Distance form watercourse, MBN, Silt content, and C/N had strong explanations for soil properties (*Fig. 9*), with Simpson index, MBN and Distance from watercourse reaching significant level (*Fig. 10*).

A more in-depth analysis using a PLS-PM showed direct and indirect effects of land use types and distance from watercourse on soil texture, soil properties, soil microbial activity, soil stoichiometric ratio and vegetation biodiversity indices (*Fig. 11*). Land use types directly affected microbial activity, soil texture and stoichometric ratio, where land use types affected soil properties indirectly through stoichiometric ratio. Distance from watercourse directly affected microbial activity and vegetation biodiversity indices, where distance from watercourse affected soil properties indirectly through vegetation biodiversity indices. The goodness of fit (GOF) was 0.560 and indicated that the model has relative good predictive power.

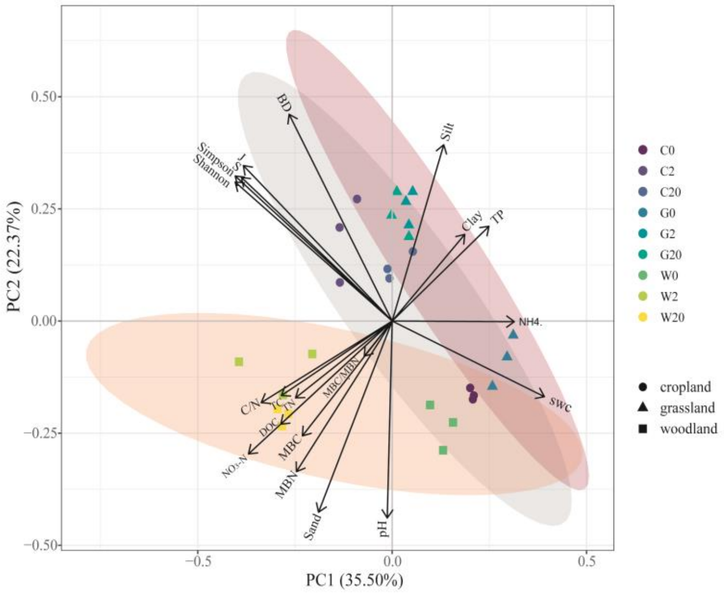

Figure 8. *PCA (principal component analysis) biplot representing the relationship between the soil physicochemical parameters and vegetation biodiversity indices in reservoir buffer strips with three land use types and distance from watercourse. Points are colored based on different site with symbols distinguishing land use types (circle = cropland, triangle = grassland, diamond = woodland). Abbreviation for soil physicochemical parameters and vegetation biodiversity indices: pH; SWC (soil water content); BD (soil bulk density); TC (soil total carbon); TN (soil total nitrogen); TP (soil total phosphorus); NH4. (ammonium nitrogen); NO_3-N (nitrate nitrogen); DOC (dissolved organic carbon); MBC (microbial biomass carbon); MBN (microbial biomass nitrogen); Sand (sand content); Silt (silt content); Clay (clay content); C/N (carbon nitrogen ratio); MBC/MBN (microbial biomass carbon nitrogen ratio); S (Richness index); Simpson (Simpson index); Shannon (Shannon index); J (Pielou index)*

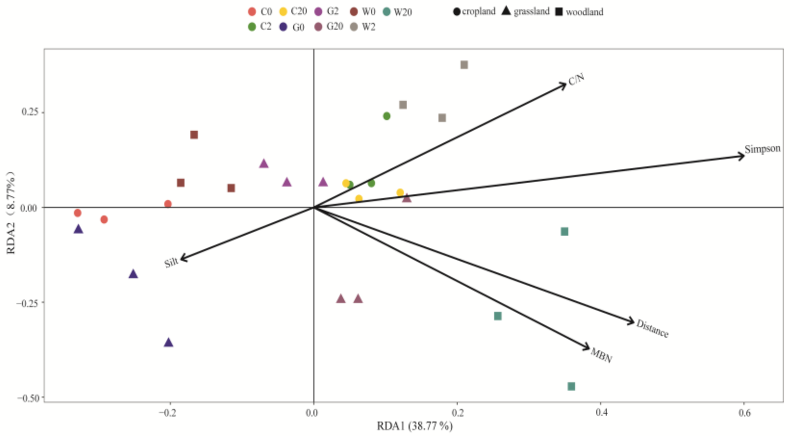

Figure 9. *RDA (redundancy analysis) using soil microbial activity, soil texture, soil stoichiometric ratio and vegetation biodiversity indices to explain variation of soil properties in in reservoir buffer strips with three land use types and distance from watercourse. The variables presented were determined by a combination of forward selection and backward selection. Points are colored based on different site with symbols distinguishing land use types (circle = cropland, triangle = grassland, diamond = woodland). Abbreviation for selected variables: Distance (distance form watercourse); Silt (silt content); MBN (microbial biomass nitrogen); C/N (carbon nitrogen ratio); Simpson (Simpson index)*

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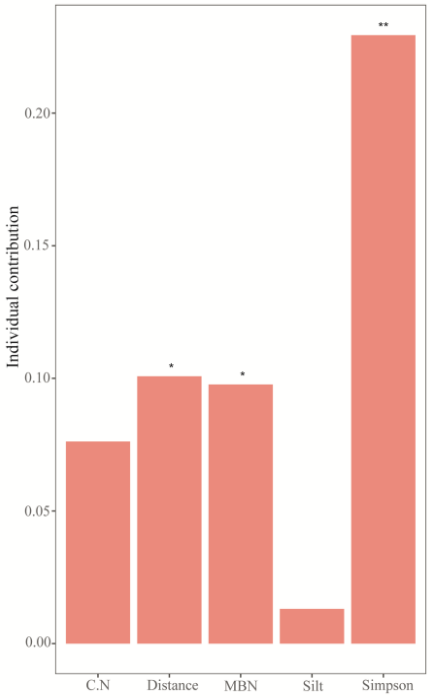

Figure 10. *The explanatory ratio and significance of variables selected from RDA. Abbreviation for selected variables: Distance (distance form watercourse); Silt (silt content); MBN (microbial biomass nitrogen); C.N (carbon nitrogen ratio); Simpson (Simpson index). * indicated significance at the 0.05 level; ** indicated significance at the 0.01 level*

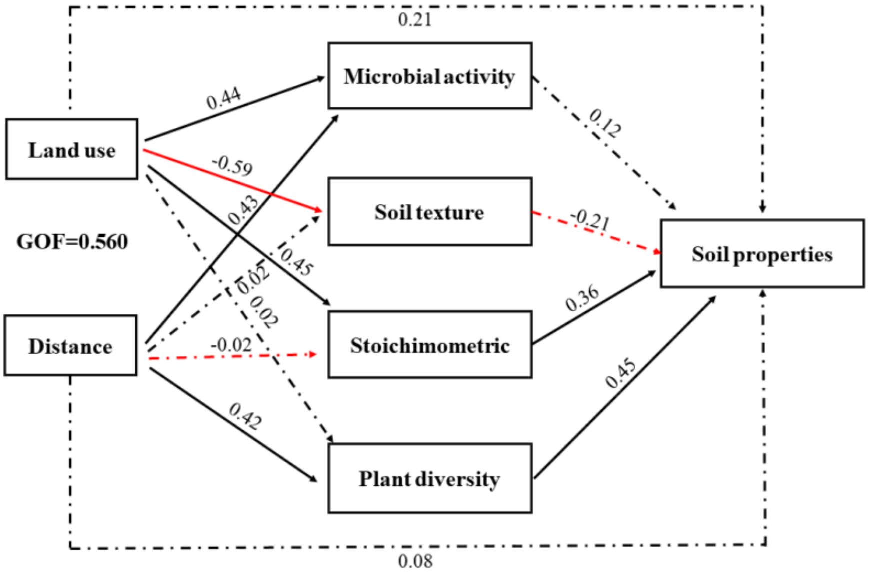

Figure 11. *The relationship between land-use types, distance from watercourse, soil texture, microbial activity, soil stoichiometric ratio, vegetation biodiversity and soil properties based on PLS-PM. Red arrows represent negative pathways. The standard path coefficients are showed on the arrow, solid line represents significant paths, dotted line represents insignificant paths. Results of model fitting: GOF = 0.560. Abbreviation: Land use (land use types); Distance (distance from watercourse); Microbial activity (soil microbial activity); Soil texture; Stoichiometric (soil stoichiometric ratio); Plant diversity (vegetation biodiversity indices); Soil properties*

Discussion

Our study focused on the differences between soil physicochemical properties and the relationship between soil physicochemical parameters and vegetation biodiversity indices at fine-scale in reservoir buffer strips with three land use types, explored the variation patterns of soil physicochemical properties at distance scales, revealed the main factors affecting soil properties, and provided new insights for understanding the newly formed reservoir buffer strips, especially in the context of weighing the contradiction between agricultural production and ecological benefits (Prastiyo et al., 2018), and provided valuable theoretical references for the management and restoration of reservoir buffer strips.

Differences of Soil Physicochemical Properties in Reservoir Buffer Strips with Three Land Use Types

As the last barrier to prevent soil nutrient loss, buffer strips play an essential role in maintaining the stability of bank line and protecting soil and water (Hickey and Doran, 2004; Smith et al., 2012; Walton et al., 2020). Therefore, understanding the complexity and spatiotemporal dynamics of soil nutrient cycling processes in reservoir buffer strips with different land use types is an important task to assess reservoir habitat quality and future ecological development (Hale et al., 2014; Whigham et al., 2017; Zhao et al., 2020). In this study, we found the soil TC and TN content in woodland buffer strips were significantly greater than grassland and abandoned cropland, indicating that woodland reservoir buffer strips had better soil carbon sequestration potential, which was consistent with the literature of Cole et al. (2020) and Hazlett et al. (2005). The woodland in this study adopted an agroforestry management system, which has been widely proven to be suitable for development in buffer strips, maximized the resolution of cost-benefit conflict, and the synergistic effect of deep and submerged root systems as well as the efficient use of light pattern indicated that the agroforestry management system can significantly improve soil carbon storage (Udawatta and Jose, 2011, 2012; Prastiyo et al., 2018). It was noteworthy that the higher TC and TN in woodland buffer strips mainly came from the contribution at W2, which may be explained in two ways. First, due to the abundance of organic matter in the surface layer of woodland soil, the raised water level due to impoundment may have accelerated the release of nutrients from the surface litter. Second, the transfer of nutrients from high elevation areas to watersheds with surface runoff may have created a hotspot of carbon and nitrogen enrichment in the waterward location (Nsabimana et al., 2020; Zhao et al., 2021). In contrast, soil TP was significantly lower in woodland than in the other two land use types, which may be mainly due to the higher carbon and nitrogen content in woodland accelerating the activation of organic phosphorus and promoting the loss of dissolved phosphorus (Zhang et al., 2013; Ye et al., 2014; Zhao et al., 2021). This may also be one of the reasons why numerous studies have showed that woodland is less capable of trapping P than grassland (Dorioz et al., 2006; Roberts et al., 2012; Kieta et al., 2018). In addition, the soil BD and SWC in woodland was significantly lower than the other two land use types, indicating that the woodland reservoir buffer strips can effectively reduce soil water content and increase surface infiltration, which was consistent with the result of Anderson et al. (2009).

Carbon and nitrogen pools are important factors affecting the soil nutrient cycle, and the mineralization of carbon and nitrogen can influence the amounts of ammonium and nitrates in soils (Tinker and Nye, 2000; Wei et al., 2017). Studies have shown that woodland vegetation can provide more deep organic matter than grassland, can effectively promote denitrification, and can have a stronger ability to reduce nitrates (Batlle-Aguilar et al., 2012; Wei et al., 2017). However, in this study, woodland soils were characterized by low NH_4-N and high NO_3-N, which may be due to the fact that water impoundment provides an anaerobic environment for abandoned cropland and grassland, promoting denitrification and accelerating nitrate depletion. The higher porosity of woodland and better diffusion of oxygen in air-filled soli pores can inhibit denitrification and hasten the accumulation of nitrate (Baldwin and Mitchell, 2000; Marschner, 2021).

Studies have shown that increases in MBC and MBN are related to the availability of soil carbon (C) and nitrogen (N) sinks (Cao et al., 2008) and that the decomposition rate of organic matter determines the change level of microbial C and N (Schnürer et al., 1985). In this study, the MBC, MBN, and DOC contents of woodland soil were significantly higher than those of abandoned cropland and grassland, which indicated that the woodland soil has well microbial activity. This may be attributed to two explanations. First, woodland have a more advanced root structure than abandoned cropland and grassland that protect the soil from erosion and was more conducive to microbial biomass accumulation (Lennon et al., 2012). Second, woodland soil had a better aeration environment that was conducive to the activity of aerobic microorganisms and thus enhanced the accumulation of microbial biomass (Jing et al., 2020). The higher MBC, MBN, DOC content in the woodland at W20 also seem to support the above speculation.

Ecological ratio constitutes an intrinsic link between biogeochemistry and the structure and processes of food webs and are the result of the interaction of multiple chemicals in the ecosystem, reflecting the ecosystem’s nutrient use strategy (Yao et al., 2019; Yu et al., 2020; Zhu et al., 2022). Soil C/N, MBC/MBN are usually considered to be relatively stable without large range fluctuations and are important indicators of ecosystem stability (Li et al., 2020). C/N is an indicator of N mineralization capacity and reflects the decomposition of soil organic matter. Low C/N (<25) indicates that the rate of organic matter decomposition is greater than the rate of accumulation (Bui and Henderson, 2013). In this study, soil C/N of the woodland buffer strips was significantly greater than the other two land use types, which indicated that the woodland buffer strips had higher soil organic matter retention capacity. In addition, the C/N of all land use types were lower than 12, which indicated that the soil nutrient status in the reservoir buffer strips with three land use types were in an environmentally constrained condition (Ye et al., 2014, 2019); MBC/MBN is usually considered as an effective indicator of nitrogen availability, and the lower the MBC/MBN, the higher the nitrogen availability (Cleveland and Liptzin, 2007; Ma et al., 2017). The strong correlation relationship between stoichiometric ratio and NO_3-N in this study also provided direct evidence. Meanwhile, the MBC/MBN of the grassland was significantly lower than the other two land use types, which indicated higher soil nitrogen availability in grassland.

Variation of Soil Physicochemical Properties at the Distance from Watercourse in Reservoir Buffer Strips with Three Land Use Types

The effect of distance from watercourse on riparian ecosystem is mediate through the underground water level, the higher the underground water level, the more easily the vegetation and soil above are contacted with water, which in turn affects the soil chemical processes and vegetation survival strategies (Lu et al., 2018; Xia et al., 2018; da Silva et al., 2021). The effects due to hydraulic gradient are more clearly defined at large scales and are still limited at fine-scale (Bao et al., 2015; Xia et al., 2018; Ye et al., 2019). da Silva et al. (2021) proposed that the distance from watercourse and the gradient of nutrient variation were the most important factors influencing the assemblage structure of pteridophyte in tropical forest at fine-scale (< 50 m). In the present study, we found that most of the nutrient did not seem to have a clear pattern of variation on the fine distance scale. While the results from our PCA analysis showed that the soil physicochemical properties at 0m were relatively similar for three land use types, which may be due to the fact that the soil at this location was directly inundated with water and was thus more influenced by the nutrient status of the overlying water (Ran et al., 2020b). Without considering 0 m, we found that some soil nutrients showed a significant trend at distance scale. For example, soil TC and TN of three land use types gradually decreased with increasing distance for watercourse which was consistent with the previous literature (Xia et al., 2018; Zhao et al., 2020), although this difference was not significant in abandoned cropland and grassland. Meanwhile, the effects of distance from watercourse on MBC, MBN, NH_4-N all reached significant levels (Two-*ANOVA*). The results of RDA analysis also indicated that distance from watercourse was an important factor affecting the reservoir buffer strips at fine-scale. All of the above results indicated that the distance from watercourse is still a non-negligible factor on soil physicochemical properties at fine-scale (especially for sheltering measures such as buffer strips).

Relationship between Soil Physicochemical Properties and Vegetation Biodiversity in Reservoir Buffer Strips with Three Land Use Types

Soil properties are the external integrated manifestation of the interaction processes of various biotic and abiotic factors, and changes in soil texture, microbial activity, stoichiometric characteristics, and vegetation community structure can have profound effects on soil properties (Stutter and Richards, 2012; Zhao et al., 2020; Liu et al., 2021). Hu et al. (2022) confirmed that the soil and microbial biomass stoichiometric is influenced by plant communities and soil properties in the mangrove forest. Therefore, clarifying the relationship between soil physicochemical properties and vegetation in reservoir buffer strips with different land use types and revealing the key factors affecting soil properties can provide a basis for the management and restoration of reservoir buffer strips (Zhao et al., 2020; Hu et al., 2022). In the present study, the effect of land use types on soil properties was achieved indirectly through soil stoichiometric ratio, which suggested that reservoir buffer strips with different land use types keep the relative constancy of soil physicochemical properties by maintaining stable stoichiometric characteristic. The effect of distance from watercourse on soil properties was moderated by the vegetation biodiversity indices, and although the trend of the vegetation biodiversity indices was not significant at the distance scale, the strong correlation between the vegetation biodiversity indices and soil physical properties (SWC, BD) indicated that changes in vegetation biodiversity due to hydraulic gradient modulated the variation of soil properties in the reservoir buffer strips. The results of the RDA analysis also showed that the Simpson index and distance from watercourse were the two major factors influencing soil properties.

In addition, without considering the above-mentioned 0m, there seemed to be a different mechanism for the changing pattern of soil physicochemical properties in the reservoir buffer strips with three land use types, and the results of the PCA analysis showed that the woodland have strong correlation with most of the soil chemical property parameters, microbial activity, and stoichiometric ratio characteristic, while the abandoned cropland and grassland had strong correlation with the soil physical properties and vegetation biodiversity indices, which may be due to the fact that the soil of woodland maintains relative well soil aeration, promoting soil microbial activity and accelerating nutrient turnover (Wang et al., 2010, 2018). In contrast, abandoned cropland and grassland have been subjected to the influence of water impoundment, their soil pores have been filled with water, their soil aggregates have become fragmented, and soil physical properties have become the dominant factor affecting soil nutrient status (Six et al., 2000; Ran et al., 2022).

Combining the above results, we can speculate that the existing buffer strips width of abandoned cropland and grassland do not seem to meet the needs of ecological restoration and should be appropriately widened. This was also in line with the proposal by Cole et al. (2020) that the width of riparian buffer strips should be set flexibly according to the land use.

Simultaneously, combining the results of RDA and PLSM analysis indicated that MBN is a main factor affecting soil properties, and both land use type and distance from watercourse directly affect soil microbial activity. It seemed microbial activity to be an important indicator of soil physicochemical properties in reservoir buffer strips with different land use types, which was consistent with the result of Ran et al. (2022) in the Three Gorges Reservoir riparian zone with different land use.

Conclusion

Soils are not only an important repository of ecosystem biodiversity but provide a wide range of other functions (e.g., nutrient cycling, waste decomposition) and services (e.g., climate regulation, pathogen resistance), as well (Guerra et al., 2021). Understanding the complex dynamics of soil nutrient cycling processes, and thus characterizing the extent to which various potential soil indicators change in the absence of restoration, and the magnitude at which these changes occur, can help determine which indicators may be most useful for effective monitoring of reservoir buffer strips in the future (Hale et al., 2014).

In this study, we reiterated the critical role of distance from watercourse on the heterogeneity of soil physicochemical properties in the buffer strips, both at large and fine scales. Wooded buffer strips have obvious advantages over other land use types in maintaining soil microbial activity and promoting soil carbon sequestration potential. Therefore, forestry measures should be given priority consideration in the process of reservoir buffer strips ecological restoration. Meanwhile, the width setting of reservoir buffer strips should be appropriately increased (>20 m) in the case of restoration based on grassland and abandoned cropland. Soil microbial activity can be used as an important indicator for monitoring the soil nutrient status of different land use types in the reservoir buffer strips. However, these results were based on short-term preliminary investigations, and long-term monitoring of the coupling and decoupling mechanisms between soil physicochemical properties and vegetation needs to be carried out.

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Conflict of Interests. The authors declare that they have no conflict of interests.

Author Contributions. YK conceived and SH designed the experiment; TY performed materials and data analysis; TY wrote the paper; TM and AM revised the manuscript.

Data Accessibility. The data that support the findings of this study are openly available in the Dryad Digital Repository. Doi: 10.5061/dryad.nk98sf7vq.

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