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The Influence of Harbin Forest–River Ecological Corridor Construction on the Restoration of Mollisols in Cold Regions of China

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Abstract: Artificial ecological corridors (AECs) are internationally approved ecological restoration and climate mitigation strategies. The width and recovery time indices of AECs directly affect the restoration efficiency of degraded soil nutrients. However, there is a lack of comprehensive and quantitative evaluation research on the construction factors of AECs from the perspective of soil fertility improvement. This research aimed to examine the critical ecological corridor construction factors affecting Mollisols' eco-chemometrics and give a scientific scope. We collected 55 Mollisol samples at different restoration years (0–35 years) and different distances (0–280 m) from the AEC of the Ashi River, a typical Mollisol restoration area in Harbin, and the cold regions of China. We measured the distances, restoration years, soil thickness, pH, electrical conductivity (EC), cation exchange capacity (CEC), soil total organic carbon (SOC), soil total organic matter (SOM), dry matter content (DMC), and the proportion of nitrogen (TN), phosphorus (TP) and potassium (TK). The results are as follows: (1) Within the AEC, there were significant differences in soil stoichiometric characteristics in different restoration years and locations; after restoration for 10–35 years, the soil stoichiometric characteristics reach or exceed the reference value of Mollisols. (2) It is feasible to restore large-scale degraded Mollisols through ecological corridors. In this recovery process, the soil nutrients first decreased, then increased, and finally reached and exceeded the reference value of normal Mollisols. (3) Soil nutrient accumulation was related to ecological corridor width and recovery time. The recommended unilateral width of the ecological corridor based on Mollisols' CEC and SOC indices for restoration is 175–225 m, and the restoration period is 22.7–35 years based on Mollisols' EC and SOC indices for restoration. This study demonstrated the change mechanism of Mollisols in AECs based on recovery time and location, and provided the basis for the Chinese government to formulate policies for Mollisol remediation.

Keywords: cold regions; ecological corridor; land use type change; Mollisols

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1. Introduction

The Mollisols, cultivated forest–grasslands ecosystems, are a soil resource with high natural fertility, and are one of the ecosystems with a high ecological service function and value. The total area of Mollisols cultivated in the world is about 4.88 × 106 km^2 [1], accounting for one-third [2] of the total cultivated land in the world. Mollisols are a valuable agricultural resource and have a huge agricultural production potential. They have developed into important global food-producing regions. These areas guarantee the world's food security and are called "the granaries of the world" [3]. The Mollisol belt in Northeast China is one of the three major Mollisol regions globally [4], but due to the single function of this ecosystem, it is prone to ecological and environmental problems such as pests and diseases, soil fertility decline, soil compaction, and soil erosion [5].

The protection of environmental elements by constructing corridors and sources is an effective means of protecting the fragile ecological resources in landscape ecology, which has been an important topic for international research. Today, human activities, including the expansion of urban and agricultural land, reduce biodiversity and compromise the integrity of ecological corridors [6]. As of 2020, one-third of the planet's key biodiversity areas lack any coverage, and less than 8% of the land is protected and connected by local governments [7]. At present, the internationally research on the construction of ecological corridors mainly focuses on the re-establishment of animal diversity [8,9], restoration of plants [10,11], prevention of soil loss [12,13], and evaluation of ecological conservation effects [14]. Research metrics include the choice of construction location of the corridor [15] and multiple construction factors of the corridor itself. In the study of the construction factors of the corridor itself, there are guides for the minimum width and restoration period for goals such as protecting animals [16,17] and plant restoration [18]. In the 1970s, Northeast China began to vigorously develop the forest corridor shelterbelt system to improve Mollisols' agro-ecosystems resilience and erosion resistance. After 45 years of development, a forest corridor shelter forest system of 36.707 million hectares has been formed on Mollisol farmland in Northeast China [19]. The construction of the forest corridor shelterbelt system has played an important role in improving the ecological environment of China's Mollisol regions, Existing studies [20] have proved that forest ecosystems have the highest sequestration rate of SOC in soil fertility indicators (0.43 $\text{Mg}\cdot\text{hm}^{-2}$ year^{-1}). In addition, Dong's research [21] proved that artificial forest ecosystems have a better ability to sequester soil carbon and nitrogen and improve soil aggregates than artificial grasslands. Current research shows that ecological corridors can increase vegetation coverage, improve the ecological environment, and prevent soil erosion [22–24]. However, in previous studies, there is a lack of comprehensive and quantitative evaluation research on the relationship between the construction factors of ecological corridors and Mollisol quality from the perspective of soil fertility improvement, and a unified theory has not yet been formed to guide the development of Mollisol ecological restoration corridors [25]. In cities and their surrounding areas, ecological corridors that meet the minimum width and recovery period indicators can often quickly and comprehensively complete the restoration of ecosystem. The restoration effect of the ecological corridor has a strong relationship with the recovery time and construction width of the corridor. However, there are few studies on selecting the minimum width and recovery time of ecological corridors with respect to the restoration of soil quality specifically, especially in cold Mollisol regions.

In the investigation and evaluation of soil quality, we often conduct quantitative research through ecological stoichiometry. Soil ecological stoichiometry mainly refers to the relationship of carbon, nitrogen, and phosphorus. Ecological stoichiometry studies can reveal the chemical transformation theory of nutrients in ecosystems and the nutrient regulation mechanisms between components of soil ecosystems. These metrics help deepen our grading evaluation of soft soil quality, accurately judge the changes in the components of soft soil, and quantify the increase or decrease of nutrient elements flowing into and accumulating in the soil ecosystem, caused by changes in the surrounding ecological environment [26–28]. The focus of Mollisol research has traditionally focused on ecological stoichiometric research and classification evaluation of Mollisol quality [27]. The evaluation standard primarily adopts the soil nutrient standard of the "Second National Soil Census" in China, but there are many international standards. The more widely used are Singapore's "Specification for Soil Mixtures for General Landscape Use" [29], the British "Specification for Topsoil and Requirements for Use" [30], and the United States "Standard Specification for Topsoil for Landscaping Purposes" [31]. The soil eco-chemical indicators selected in the international standards have a high degree of similarity. The majority measure pH value, soil organic matter content, electrical conductivity, total organic carbon, dry matter mass, total potassium, total phosphorus, and total nitrogen, with variation according to different research purposes.

In the minimum set of indicators for soil evaluation, studies have shown that C, N, K, and P in the soil are important components of soil nutrients and the soil elements that affect the growth of crops [32,33]. They are mainly exchanged between the soil and the surrounding ecological environment [34]. Therefore, by studying the coordination mechanism between the soil quality and ecological corridor construction factors, based on ecological stoichiometry, we can clarify the impact mechanism of ecological corridor construction on the soil quality. In addition, the mechanism and scope of influence of the corridor construction factor on the improvement of Mollisol quality can also be clarified.

Previous studies on the construction factors of ecological corridors mainly focused on rare animal protection and habitat restoration from changes in corridor construction factors. For example, Schalkwyk [35] monitored arthropods and found that larger ecological corridors have a greater conservation value than smaller corridors. In addition, the article recommends restoring some wide corridors in the narrow forest belts surrounding the productive landscape therein, for a given area of under-protected land that needs to be preserved. Closet-Kopp [36] demonstrated that the quality of ecological corridor habitats increased with increasing width, height, and age of hedges. An empirical study by Javiera [37] pointed out that ecological corridors with a width of fewer than 10.5–95 m had a forest fragmentation effect, and under this, the entry of predators and consequent bird diversity decreases. Li, Yuwu's [38] compared the soil in a rubber forest, a wildwood forest, and the Asian elephant protection corridor of the Mekong River, and found that it took about 100 years for the rubber forest to restore the soil to the normal soil level, but implementing the Asian elephant ecological corridor restoration process on rubber forest soil could shorten the recovery time to about 40 years. It is evident that the width and restoration period of ecological corridors are important variables in the restoration of Mollisols.

There is no doubt that there is a feedback mechanism between the quality of the ecological environment in a corridor and its construction factors. The quality of animal protection and habitat restoration (the construction factors of ecological corridors) are relatively well studied in temperate and tropical terrestrial ecosystems [14]. However, little is known about the relationship between soil ecological stoichiometry and ecological corridor construction factors in ecological corridors, especially for places with an urgent need for soil protection, such as is the case in the Mollisol farming area in Northeast China's cold region. Therefore, we speculate that the ecological stoichiometric relationship with the two corridor construction factors of width and restoration period in the Mollisol environment is an important influencing factor for the restoration effect.

This study is significant for further understanding the nutrient balance and dynamic changes of the Mollisol ecosystems in northeast China. We evaluated the relationship between the construction factors of the ecological corridor itself and the soil ecological stoichiometry. We sampled the different distances from the Ashi River ecological corridor. In the experimental area, the distribution of plants is relatively uniform. The trees are an artificially planted fast-growing tree species in northern China, including elm (*Ulmus pumila Linn.*) and poplar (*Populus tomentosa Carr.*). The shrubs are mainly forsythia (*Forsythia suspensa* (*Thunb. Vahl*) and elm plum (*Amygdalus triloba* (*Lindl.*) *Ricker*), and the soil is chernozem. The local area is a typical Mollisol cultivation area with more than 70 years of cultivation history. Compared with the ordinary chernozem soil, the eco-chemical indicators of the Mollisol are degraded to varying degrees [39]. Sampled soils were analyzed physical and eco chemical indices of the soil samples were measured and we constructed the model relationship between them. We analyzed the distribution characteristics of the soil eco-chemical indicators in different locations and number of restoration years in the ecological corridors in the Mollisol area, and constructed the model relationship between them. Then, we determined the key ecological construction factors affecting soil quality in the corridor and identified the optimal width and number of years of ecological corridor restoration for the key indicators. This study extends our understanding of the mechanisms of ecological corridor restoration of Mollisols and the restoration of soil nutrients and provides a theoretical basis for formulating ecological corridor construction strategies for Mollisol restoration in northeast China.

2. Materials and Methods

2.1. Study Site

The Volga Manor section of the Ashi River ecological corridor in Harbin (125°42′~130°10′ E, 44°04′~46°40′ N) is located in the central part of the Heilongjiang Province, with a monsoon climate in the temperate zone (Figure 1a). The annual average precipitation is 569.1 mm, which is concentrated from June to September. Summer accounts for 60 percent of the annual precipitation with a concentrated snowfall period from November to January. The four seasons are clear, and the average temperature in January is minus 19 °C; the average temperature in July is about 23 °C. The selected sampling area is about 2.6 km (Figure 2).

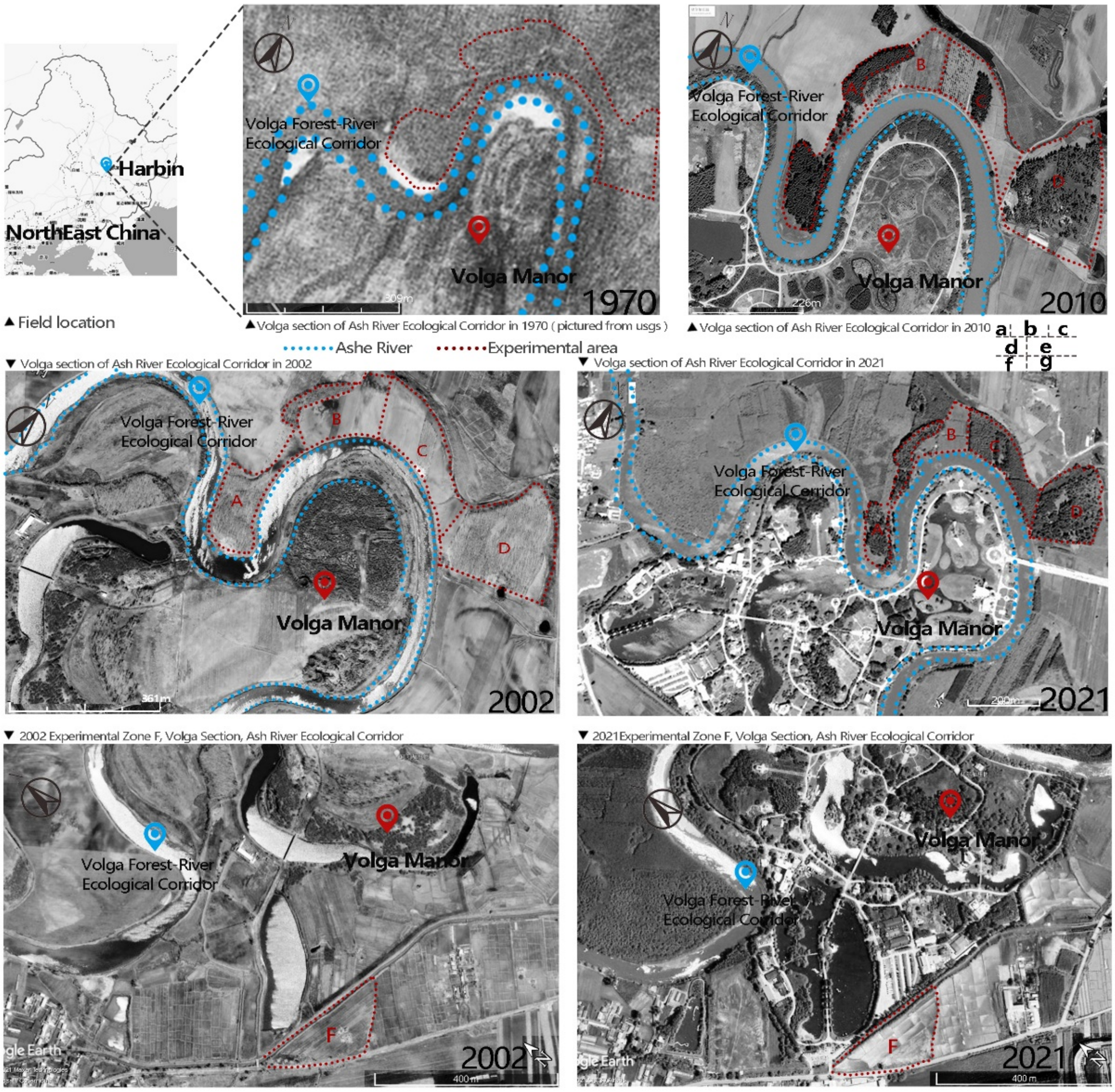


Figure 1. The number of years of recovery for all samples studied was based on local maps, historical archives, aerial photographs, and field surveys (photographs from USGS and CNES/AIRBUS). (**a**): Field location, (**b**): Volga section of Ash River Ecological Corridor in 1970 (pictured from usgs), (**c**): Volga section of Ash River Ecological Corridor in 2010, (**d**): 2002 Experimental Zone F, Volga Section, Ash River Ecological Corridor, (**e**): 2021 Experimental Zone F, Volga Section, Ash River Ecological Corridor, (**f**): 2002 Experimental Zone F, Volga Section, Ash River Ecological Corridor, (**g**): 2021 Experimental Zone F, Volga Section, Ash River Ecological Corridor.

Figure 2. Distribution of 57 sampling points in the study area.

Using historical data, USGS maps (1970) and aerial images from 1985 to 2021 (Imagine @ CNES/AIRBUS), we constructed a time series of the corridor: from 1 to 35 years (for more details about the method of determining the age of the corridor from the old image, see Jonathan Lenoir's study [40]). For the ecological corridors appearing between the two continuous historical maps, we took the median date between the two aerial images, combined with the plant age on the spot and the survey method of asking farmers to accurately date the first appearance of the corridors and plants in different sections. Based on the existing image, historical data and a field survey, we determined the number of recovery years of the soil samples (Figure 1).

The reasons for selecting this section of the forest–river ecological corridor for sampling are as follows: First, the Ashi River ecological corridor is located in the Mollisol belt of Northeast China. The Mollisol land in the Volga Manor region has a long cultivation period of more than 50 years. The cultivation method was by private contracted farming, a typical method for cultivated land in Northeast China. Second, the topography of the sampling site was relatively flat, which is consistent with the topography of most cultivated Mollisol land in the northeast Mollisol belt. Third, the sampled sites were adjacent to the Ashi River. The sites were all inside the forest belt on both sides of the ecological corridor, which was convenient for comparative study of the effect of the ecological corridor of the Ashi River on the Mollisols. Finally, the Ashi River forest–river ecological corridor restored each section successively, in around the year 2000 (Figure 1d). In 2010, a government document [41] was officially issued to support the restoration. It is one of the five typical river ecological corridors in Harbin that had a focus on supporting the restoration. It connected and restored the Xiquanyan Reservoir of the Ashi River and the estuary of the Songhua River, two animal habitat areas of high ecological quality. The river course is about 140 km, and the drainage area is 2431 km^2. Volga Manor has a long recovery time, good research foundation, and a good representation of the Mollisol cultivated land restoration.

Ideally, to measure the impact of ecological corridor construction on Mollisol cultivated land, we should measure it before or when the corridor is constructed, and then measure it at the same location after 2 years, 5 years, 10 years, 20 years, 30 years, and 40 years. However, since the soil was not measured 50 years ago, we used the 'time and space' method [42]. The site was selected to represent a range of time periods from active agricultural use to 40 years after restoration. Although based on a cross-sectional design, it mimics a longitudinal study. Part of the research area has been restored from agricultural use to ecological corridors (sampling sites A, B, C, D, and E). In contrast, an adjacent area is still used for agriculture (sample site F). Elevation, climate, and soil factors were the same across the study area. Planting was the main difference in the land-use history, and there were no other interference factors near the artificial ecological corridor.

2.2. Soil Sampling and Analysis

Figure 2 shows detailed satellite photos of the sampling points. The sample plots A–E were divided into 50 m × 50 m grids, and if the area of the grid at the edge of the plot was less than 50 m × 50 m, no sampling point was set (Figure 2). Plot A was divided by the grid method (50 m × 50 m), and 24–42 sample points were randomly selected among them; its recovery time is more than 20 years; Plot B, C, and E adopted the grid method (50 m × 50 m) and were divided and 10–23 sample points were randomly selected within this area; its recovery time is between 1–18 years. (The forest in sample plot C in Figure 1c had been restored, and the specific recovery time of the sample site was based on the plants in the site and consultation with the surrounding farmers); After the sample plot D was divided by the grid method (50 m × 50 m), sample points 1–9 were randomly selected; its recovery time is more than 20 years. (Sample D in Figure 1d already had forests in 2002, and the specific recovery time of the sample site was based on the plants in the site and consultation with local farmers). Sample plot F was basic farmland and the farming method is mechanized. We found that the disturbance factor of the farmland was much greater than that of the ecological corridor. Therefore, we reduced the spacing of the sample points to 1 m to show the farmland changes in more detail with 43–57 randomly set sample points. The continuous tillage period was more than 50 years (Figure 1f,g) with a recovery time of 0 years. Each soil sample was composed of a center point and a circle located in the radius of 10 m and three vertexes of the triangle above the circle to form a soil sample of about 1 kg. Soil samples were dried and stored at 4 °C in a refrigerator.

The method for measuring comprised physical and chemical indices is as follows: For the physical index, a soil sampler drilled the thickness of the Mollisols. After the Mollisols were mined, the depth was measured. For the chemical indices, we determined the total carbon (Tot-C), total organic carbon (SOC), organic matter (SOM), nitrogen (TN), phosphorus (TP), potassium (TK), pH value, soil cation exchange capacity (CEC), soil electrical conductivity (EC), and soil dry matter quality (DMC) of the soil samples. Tot-C and Tot-N were measured for dry combustion using a LECO TruSpec® CNH analyzer (LECO Europe B.V., Geleen, The Netherlands). The presence of inorganic carbon was examined by adding 10 percent hydrochloric acid to the soil samples. No foaming phenomenon was observed, ensuring that the pH value was lower than 6.5 and indicating that Tot-C in all samples could be explained by soil organic carbon (SOC) [43]. SOC was determined by colorimetry (Cytation, Biotek, Winooski, VT, USA); organic carbon was oxidized under heating conditions by potassium dichromate-sulfuric acid solution and the $Cr6^+$ in the potassium dichromate was reduced to $Cr3^+$, which was proportional to the content of organic carbon. Absorbance was measured at 585 nm to calculate the organic carbon content. SOM was measured by the potassium dichromate volumetric method (VOL). Total phosphorus was determined by molybdenum antimony colorimetry (Cytation, Biotek, Winooski, VT, USA). Soil pH was measured at a ratio of 1:2.5 v/v of soil to distilled water using a glass membrane electrode (ORION SA 720 pH/ISE). The cation exchange capacity (CEC) was determined by extraction with 1 M ammonium acetate ($NH_4CH_3CO_2$) buffered at pH = 7.00 and calculated by the sum of ${Ca_2}^+$, ${Mg_2}^+$, K^+, Na^+, and total acidity (H^+). Soil salinity (EC) was determined by the conductivity method. After extracting the aqueous solution with a water–soil ratio of 5:1, a portable conductivity meter (DDS-307A, Shanghai, China) was used to determine conductive. After drying, soil matter (DMC) was weighed.

2.3. Data Analysis

SPSS v22.0 for Windows software was used for a one-way analysis of variance to compare the differences in soil physical and chemical properties of different land types, recovery years (0 years, 2 years, >10 years), and distances from the Ashi River (0–280 m). We clarified the key ecological corridor construction indicators affecting soil eco-metrology using a redundancy analysis (RDA). RDA allows the regression of multiple dependent variables (CEC, EC, SOC, and SOM) on multiple independent variables (distance and recovery time). Finally, both single and multiple linear regressions were carried out to determine the contribution of environmental factors on soil indicators, and the most suitable ecological corridor construction index was selected. All statistical tests were performed at a 0.05 significance level. The data was visualized through Origin 2020 and R. We excluded outliers through boxplots for all collected sample data.

3. Results

3.1. The Influence of the Forest–River Artificial Ecological Corridor on Cultivated Land in Mollisol Areas on Soil Eco-Chemical indicators

Table 1 shows the soil properties of cultivated land, ecological corridors restored for two years, and ecological corridors restored for more than 10 years. The results showed that the Mollisol layer thickness of ecological corridors restored for more than 10 years was significantly higher than that of cultivated land. CEC content in the soil also significantly decreased. EC, SOC, and SOM content decreased, but the difference did not affect the quality, compared with cultivated land. EC, CEC, and SOC in the ecological corridors restored for two years, decreased significantly, compared to cultivated land. The SOM content decreased from 35.75 g/kg to 16.24 g/kg, but the difference was not significant. Compared with the restoration of the ecological corridor restored for two years, the thickness of the Mollisol layer, SOC, and SOM in the ecological corridor above 10 years was significantly improved. CEC content increased from 13.61 cmol$^+$/kg to 16.90 cmol$^+$/kg, but the difference was not significant.

Table 1. Mollisol and site properties for the ecological corridor, cultivated land, standard deviation in brackets. Lower case letters (a, b) indicate significant differences between the sites ($\alpha = 0.05$).

Indice	**Unit**	**Cultivated Land**	**Ecological Corridor (≈2 Years)**	**Ecological Corridor (>10 Years)**	**Reference Value**
Soil Thickness	cm	60.00 (1.732) ^{b}	41.70 (5.034) ^{b}	128.18 (21.90) ^{a}	60~80~100 [44,45]
pH	/	6.5390 (0.232)	7.0633 (0.085)	6.6796 (0.450)	/
Electrical Conductivity	ms/m	26.69 (8.78) ^{a}	11.63 (3.11) ^{b}	22.72 (8.88) ^{ab}	23.2 [46]
Cation Exchange Capacity	(cmol$^+$/kg)	25.15 (2.37) ^{a}	13.61 (0.92) ^{b}	16.80 (3.46) ^{b}	15~20 [47]
Dry Matter Content	%	97.26 (0.57)	98.12 (0.21)	97.93 (1.12)	/
total Organic Carbon	g/kg	20.44 (2.70) ^{a}	8.17 (1.63) ^{b}	16.27 (6.34) ^{a}	15 [48]
total Organic Matter	g/kg	35.75 (5.64) ^{ab}	16.24 (3.99) ^{b}	29.07 (12.22) ^{a}	19.5 [19]
Nitrogen	%	0.175 (0.46)	0.101 (0.37)	0.148 (0.64)	/
Potassium	%	1.92 (0.24)	2.02 (0.10)	1.923 (0.23)	/
Phosphorus	%	0.062 (0.02)	0.053 (0.004)	0.05 (0.01)	/

Cation Exchange Capacity = Cation Exchange Capacity by ammonium acetate in pH 7. The experimental site belongs to the soil-forming range of black calcium soil in Northeast China, and the reference value of the above table is the normal black calcium soil value. Sampling depth limited to topsoil (root-dense area). Ecological corridor (≈2 years) = Number of years of artificial ecological corridor restoration is 2 years; Ecological corridor (>10 years) = Number of years of artificial ecological corridor restoration is more than 10 years.

Compared with the reference value, due to the use of chemical fertilizers, the indices of the cultivated land exceeded the normal value, and the EC value was increased from 23.2 ms/m to 26.69 ms/m, indicating that the cultivated land soil showed salinization. In the ecological corridor restored for two years, the soil indices decreased significantly compared with the normal values. Among them, the decrease of the EC index from 23.2 ms/m to 11.63 ms/m indicated that soil salinization was slowed down, but the decrease of ST, SOC, and SOM indicated a substantial depletion of nutrients. Soil, EC, CEC, and SOC indices of ecological corridors restored for more than 10 years returned to normal values, and the ST and SOM significantly exceeded normal values and increased significantly.

Overall, the restoration of soil by a forest–river ecological corridor (>10 years) experienced a decline, rebound, and finally stabilized. In addition, the length of corridor recovery time of the ecological corridor had a significant effect on the changes of EC, CEC, SOC, SOM, and other biochemical indices in matrix soil.

Figure 3 shows that the distance from the Ashi River was significantly related the content of soil organic matter in the ecological corridor, and in the range of 130–180 m, the recovery effect of the SOM was the highest, reaching the maximum. The distance from the Ashi River was significantly related to organic matter and the carbon–nitrogen ratio in the cultivated land, but the difference was not significant.

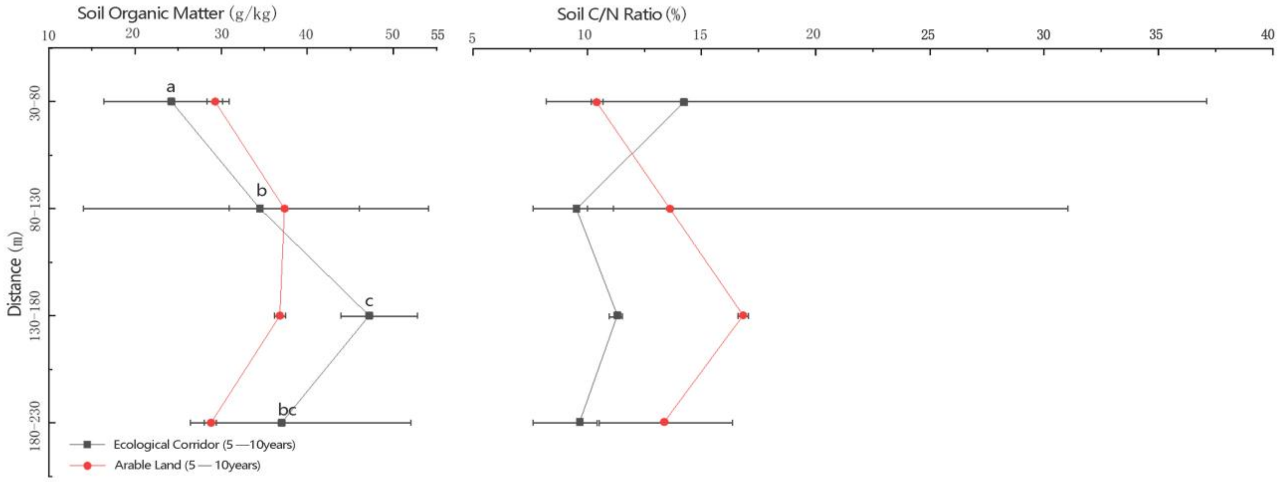


Figure 3. Soil Organic matter and C/N ratio by depth in the ecological corridor and cultivated land on Endostagnic Albeluvisol (Siltic) soil. Lower case letters indicate significant differences (α = 0.05).

We selected a distance from the Ashi River of less than 250 m but more than 30 m, because when the Ashi River is closer, especially within 0–10 m, the soil samples are affected by the rainy season floods, rainfall scouring, and other factors, and the index is unstable and a poor reference. Soil data with a stable recovery period of more than five years but less than 10 years were selected for analysis. In this period, the effect of time on the soil samples only made a minor difference.

3.2. Effects of Different Construction Factors on Soil Ecological Stoichiometric Pairs

Figure 4 shows that the correlation between the two environmental variables (SOC and CEC) was weak, with the two environmental axes present at 90 degrees. They jointly affect the soil ecological factors. Comprehensive RDA analysis of soil samples from different land-use types showed that the CEC, EC, SOC, and SOM were more correlated by the distance from the Ashi River than by the number of years of recovery. The correlation between the distance from the Ashi River and soil ecological factors was CEC > EC > SOC > SOM. We should note that the ST was highly correlated with the recovery period and was less correlated with distance.

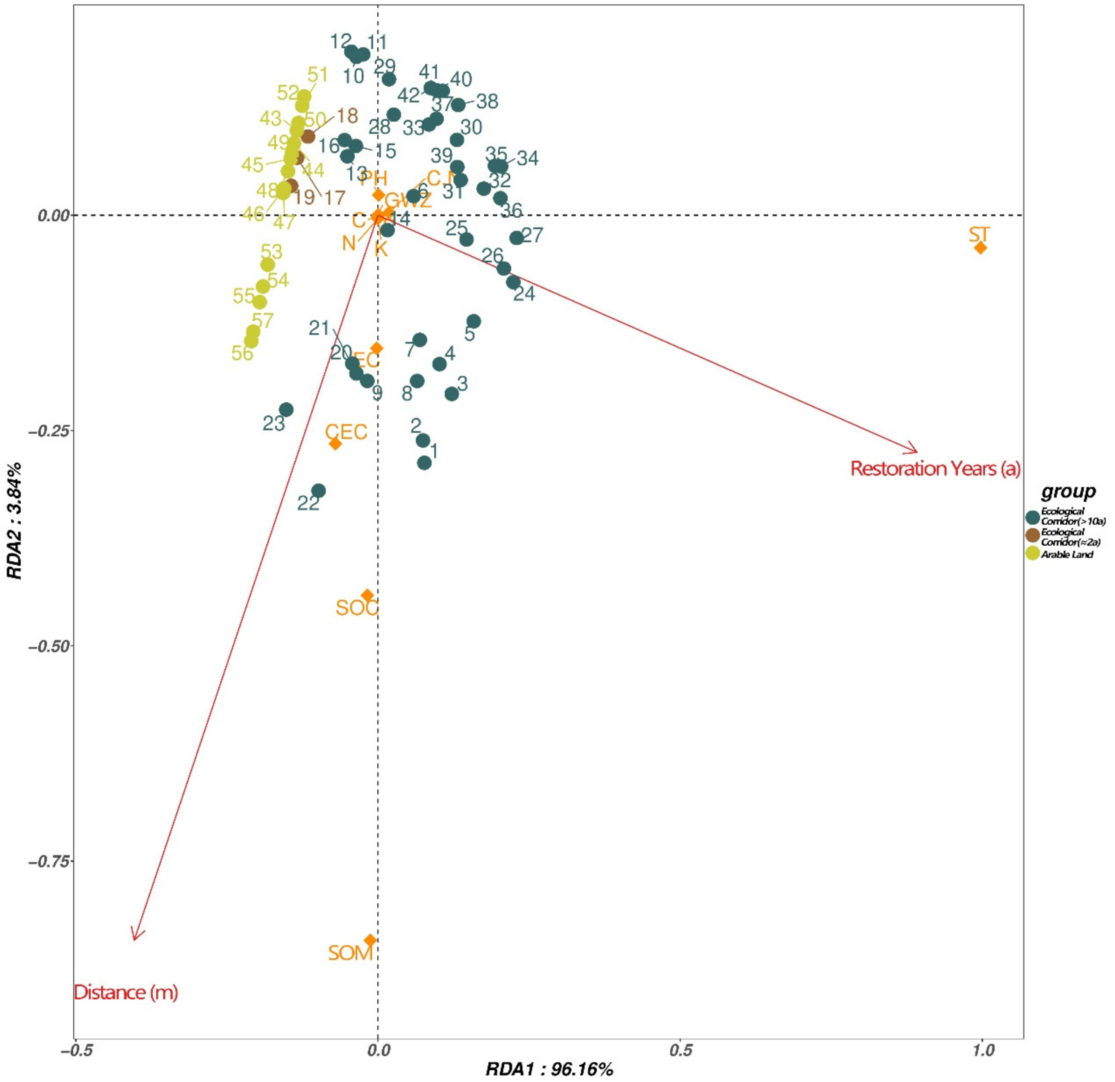


Figure 4. Soil eco-stoichiometry and the relationships between soil organic carbon (SOC), cation exchange capacity (CEC), and environmental factors in different land use situations. Red arrows indicate environmental factors. Yellow dots represent soil eco-stoichiometry. The results of the RDA analysis revealed that most of the variances in Figure 2 were represented by axis 1 (96.16%).

The sample points were divided into three categories in the RDA analysis: ecological corridor (≈2 years), ecological corridor (>10 years), and cultivated land. The distribution of the ecological corridor (≈2 years) group was nearly that of the cultivated land group, and the interior point distribution of the cultivated land group was relatively dense, indicating that under the condition of cultivated land, the ecological factors of the soil were highly disturbed by humans and the soil heterogeneity was low. For the cultivated land group, the recovery period was 0 (Figure 4). This group was only affected by the distance from the Ashi River. In the ecological corridor (≈2 years) group, with a restoration period of two years, the distribution was denser than that of the cultivated land group, which indicates that soil homogenization failed to recover in the first two years of restoration in the forest–river corridor. The distribution of points in the ecological corridor > 10 years group was relatively scattered, reflecting a high heterogeneity of points in the forest–river ecological corridor after the restoration of >10 years. At the same time, most of the points in the ecological corridor (>10 years) group were affected by the recovery period > distance from the Ashi River, and only 9, 20–23 were affected by the distance from the Ashi River > the recovery period.

3.3. Multiple Linear Regression of Soil Factors with Different Construction Factors and Contribution Analysis of Construction Factors

We selected four chemical indicators from Table 1 that had significant differences under the action of different land-use types and recovery time, for the next analysis step. CEC, EC, SOC, and SOM were selected.

Previous studies [49] have shown that the soil organic matter (SOM) is estimated by measuring the soil organic carbon (SOC) multiplied by a factor. Therefore, we chose CEC, EC, and SOC for a full subset regression analysis. In terms of data selection, we selected the sample data in the ecological corridor (>10 m from the Ashi River riparian zone), which was less affected by the other factors (Table 2).

Figure 5 shows multiple regression analysis of soil in the ecological corridor under different distances and recovery periods. For soil chemical indicators with significant differences: the main factors affecting soil cation ecological corridor width and recovery time, in 10 m < Distance to Ashi River < 300 m; in the range of 0 years < recovery time < 40 years, CEC increased with the increase of distance and recovery time. The contribution rates of distance and recovery duration were 76.3% and 32.1%, respectively. The influence of distance on soil CEC was much greater than recovery duration, which was twice that of recovery duration. The main factors affecting soil electrical conductivity were corridor width and recovery time, in 10 m < Distance to Ashi River < 300 m; in the range of 0 years < recovery time < 40 years, EC increases with the increase of distance and recovery time. The contribution rates of distance and recovery time were 19.7% and 39.1%, respectively, with a total of 58.8%. The effect of restoration duration on soil EC was greater than that of restoration duration. The main factors affecting soil total organic carbon were corridor width and recovery time, in 10 m < Distance to Ashi River < 300 m; within the range of 0 years < recovery time < 40 years, SOC increases with distance and recovery time. Distance and recovery time contributed 45.8% and 56.9%, respectively. The effect of restoration duration on soil EC was greater than that of restoration duration. Among them, in terms of the relative importance of distance, the order of influence is CEC > SOC > EC. Regarding the relative importance of recovery time, the order of influence is SOC > EC > CEC.

In the ecological corridor, we selected sample points within a recovery period of 15–35 years, and the effect of time on the soil samples was relatively consistent. The distance from the Ashi River had a greater contribution on the indicators of CEC and SOC, and the linear regression between the CEC and SOC.

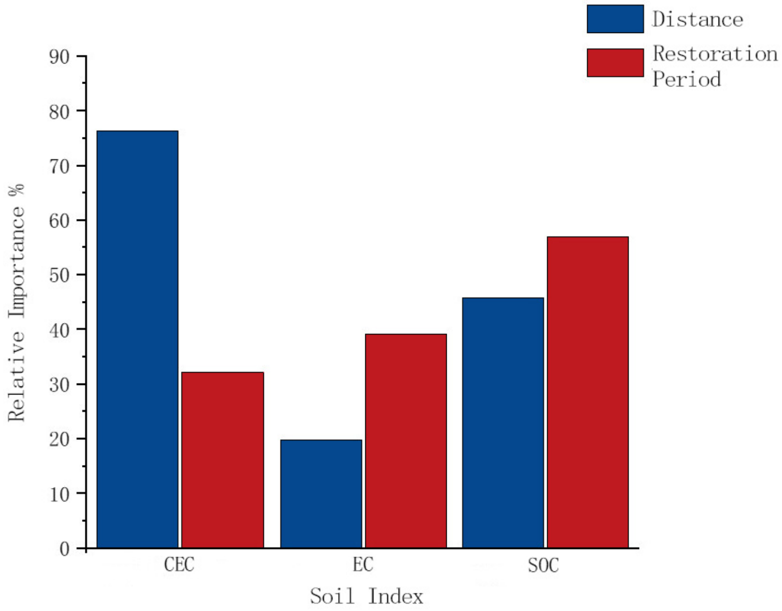


Figure 5. Relative importance of soil factors in different distances and recovery periods. CEC: soil cation exchange capacity; EC: soil electrical conductivity; SOC: soil total organic carbon.

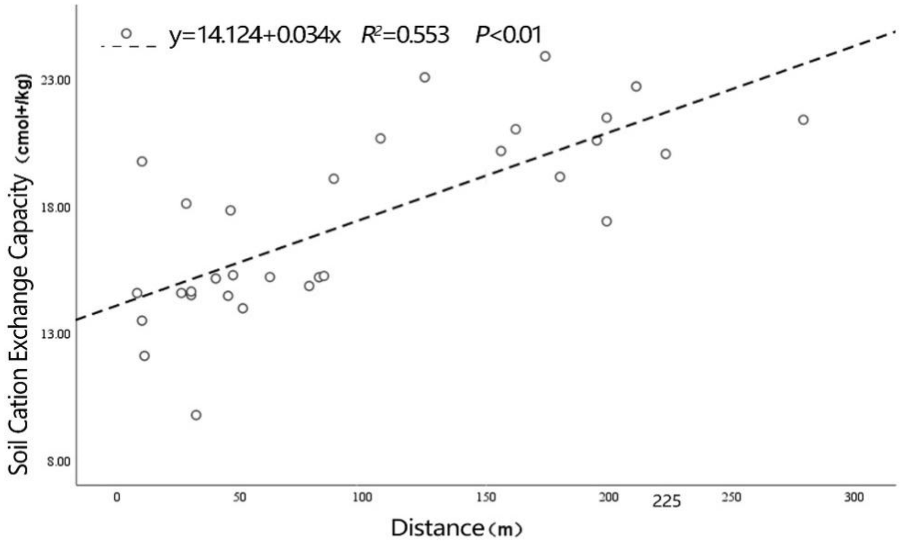
Table 2. Multiple linear regression of soil factors with different distances and recovery times (more than 10 m distance from the Ashi River, but less than 300 m, and more than 0 years recovery time but less than 40 years).

Regression	R^2	Adjust R^2	p Value
CEC = 11.180 + 0.036 × DS + 0.098 × RT	0.701	0.685	$p < 0.01$
EC = 11.695 + 0.022 × DS + 0.278 × RT	0.197	0.153	$p < 0.05$
SOC = 4.510 + 0.039 × DS + 0.315 × RT	0.551	0.526	$p < 0.01$

3.4. Selection of the Width Range and Recovery Time Range of Ecological Corridors Based on Mollisol Protection

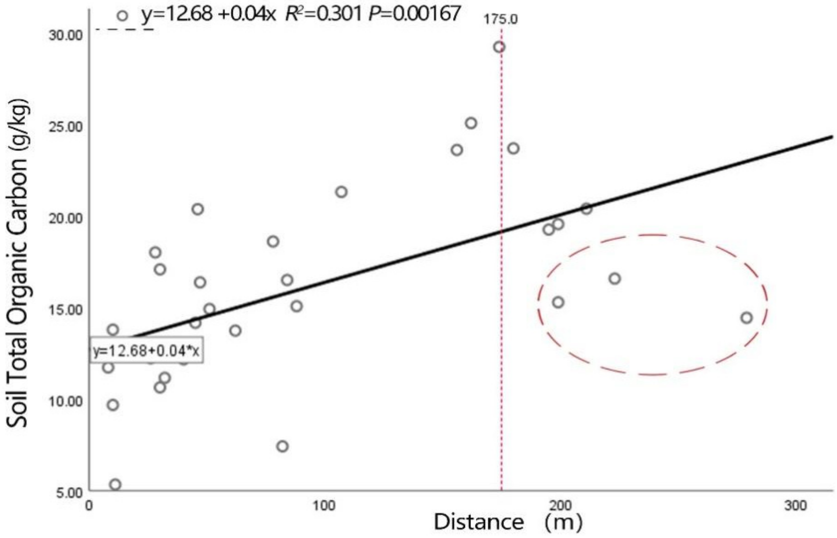
Figure 6a shows the relationship between the distance from the Ashi River and the soil cation exchange capacity. Select samples in the range of more than 10 m but less than 300 m distance from the Ashi River, and in the range of 15–35 years, were taken. With the increase in distance from the Ashi River, the cation exchange capacity in the soil increased; equation: y = 14.124 + 0.034x, $R^2 = 0.553$. In the sample analysis, within a 10–225 m distance from the Ashi River, the sample distribution was uniform, showing a positive trend. However, between 225–300 m, only one sample point was collected, showing a negative trend. We believe that where the distance from the Ashi River is >225 m, the reference accuracy of the model was reduced. Therefore, we conclude 225 m as the optimal recovery width of the CEC index.

Figure 6b shows the relationship between the distance from the Ashi River and the soil total organic carbon: selecting samples more than 10 m but less than 300 m from the Ashi River, with a recovery time in the range of 15–35 years. With the increase of distance from the Ashi River, the content of the total organic carbon in the soil increased; equation: y = 12.68 + 0.04x, $R^2 = 0.301$. In the sample analysis, where the distance from the Ashi River is within 10–175 m, the sample distribution is uniform, showing an upward trend. However, at 175–300 m from the Ashi River, the sample points collected showed an overall downward trend (within the red circle). We believe that at a distance of less than 175 m, the reference accuracy of the model is reduced. Therefore, we choose 175 m as the optimal recovery width of the SOC index, with a recommended unilateral width of the ecological corridor, based on the Mollisol CEC, SOC indices, of 175–225 m.



(**a**)

Figure 6. *Cont.*



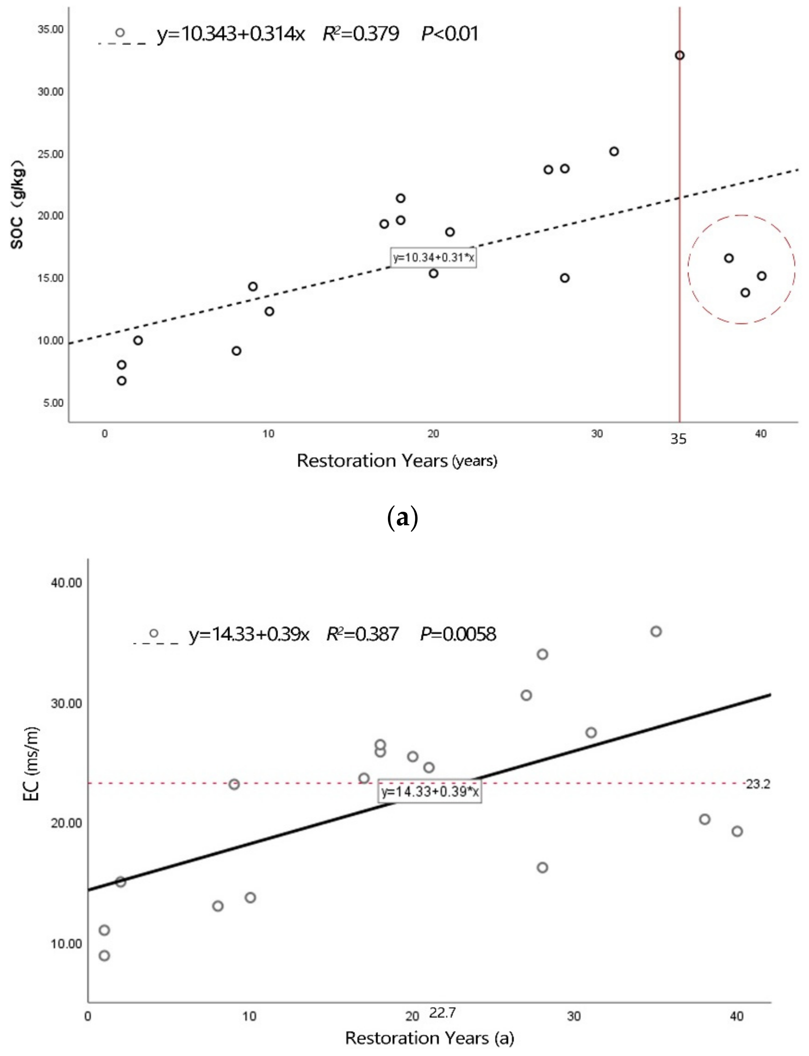
(**b**)

Figure 6. Effects of Distance from the Ashi River on soil indices: (**a**). relationship between distance and CEC; (**b**). relationship between distance and SOC (* means multiplication).

In the ecological corridor, we selected sample points between 50–200 m from the Ashi River, and the effect of distance from the Ashi River on the soil samples was relatively consistent. The recovery time had a greater contribution on the indicators SOC, EC, and its linear regression between the SOC and EC.

Figure 7a shows the relationship between the recovery time and the SOC: selecting the sample more than 50 m but less than 200 m from the Ashi River, and between 0–40 years recovery time. With the increase of recovery time, SOC content increased; equation: y = 10.343 + 0.314x, R^2 = 0.379. In the samples analyzed, within the recovery time of 0–35 years, the sample distribution was uniform, showing a steady upward trend. However, within 35–40 years, the collected sample points showed a downward trend (red circle). We believe that where the recovery time was >35 years, the reference accuracy of the model is reduced. Therefore, we choose 35 years as the optimal number of restoration years of the SOC index.

Figure 7b shows the relationship between recovery time and soil total organic carbon: selecting samples more than 50 m but less than 200 m from the Ashi River, in the range of 0–40 years recovery time. With the increase in recovery time, the soil conductivity content increased; equation: y = 14.33 + 0.39x, R^2 = 0.387. In the analysis samples, within the recovery time of 0–35 years, the sample distribution was uniform, showing a steady upward trend, reaching the normal level of soil conductivity near 35 years. Within 35–40 years, the collected sample points showed a downward trend (red circle). We believe that in the range of recovery time of >35 years, the reference accuracy of the model is reduced. Existing studies [34] suggest that 23.2 ms/m is the normal value of the EC in Mollisols, so we believe that 22.7 years is the optimal recovery period of the EC index. To sum up, The recommended restoration period of the ecological corridor based on Mollisol EC, and SOC indices is 22.7–35 years.



(**a**)

(**b**)

Figure 7. Effects of recovery time of forest–river corridor on soil indices: (**a**). Relationship between recovery time and SOC; (**b**). Relationship between recovery time and soil conductivity (* means multiplication).

3.5. Analysis of the Ecological Protection Process of Mollisols Based on the Forest–River Ecological Corridor

Table 3 shows that, in the range of 80–120 m of distance from the river, there were significant differences in the four indicators of EC, CEC, SOC, SOM, and TN between the corridors and cultivated land at two years of restoration. Within the above distance range of corridors restored for two years, all indices of the sample decreased significantly. Compared with the samples recovered for two years in the corridor and the samples of cultivated land, in the equal quality sample (ESM) analysis, in terms of the total nitrogen index, there were significant differences between all indicators, and all indicators decrease significantly. According to the field survey, fast-growing tree species such as transplanted poplar and elm covered the forest–river corridor two years before artificial restoration, which resulted in a large absorption of soil nutrients. In addition, leaf litter was less, soil cover was insufficient, and rainwater greatly impacted the soil, resulting in the loss of soil nutrients. Among them, the decline of the EC index shows that the high salinity in Mollisols was alleviated in the previous two years after the conversion of cultivated land into the artificial ecological corridor.

Table 3. Recovery of two years: corridor and cultivated land indicators. Standard deviation given in brackets, lowercase letters indicating significant differences ($\alpha = 0.05$).

Selection of Soil Samples	Electrical Conductivity (ms/m)		Cation Exchange Capacity ($cmol^+/kg$)		Total Organic Carbon (g/kg)		Total Organic Matter (g/kg)		Nitrogen (%)	
	Ecological Corridor (≈2 Years)	Cultivated Land	Ecological Corridor (≈2 Years)	Cultivated Land	Ecological Corridor (≈2 Years)	Cultivated Land	Ecological Corridor (≈2 Years)	Cultivated Land	Ecological Corridor (≈2 Years)	Cultivated Land
80–120 m	11.63 (3.11) ^{b}	28.40 (9.02) ^{a}	13.61 (0.92) ^{b}	25.94 (1.91) ^{a}	8.17 (1.63) ^{b}	21.26 (2.36) ^{a}	16.24 (3.99) ^{b}	37.36 (5.08) ^{a}	10.13 (3.66) ^{b}	17.74 (5.16) ^{a}
ESM	11.63 (3.11) ^{b}	26.69 (8.78) ^{a}	13.61 (0.92) ^{b}	25.15 (2.37) ^{a}	8.17 (1.63) ^{b}	20.44 (2.70) ^{a}	16.24 (3.99) ^{b}	35.75 (5.64) ^{a}	10.13 (3.66)	17.5 (4.6)

Equivalent soil mass (ESM). In this item, under the condition of determining the recovery time (0 years and 2 years), the distance range of the sample points is further narrowed to reduce the influence of distance on the results, the sampling points in the area with relatively uniform distance in the corridor within 80–120 m were selected for analysis. ecological corridor (≈2 years) = The recovery time for the sampling site is about two years.

4. Discussion

4.1. Effect of a Forest–River Ecological Corridor on the Fertility of Mollisols

We believe the large-scale ecological restoration of Mollisols through forest–river ecological corridors is feasible and effective. According to the standard grade for cultivated land quality in China [50], the quality grade for cultivated land in the central and northeastern regions, scholars such as Song Ge [51] and Yao Dongheng [52], and the classification standard formulated by the research on Mollisols in Harbin, we find that the cultivated land in the study area belongs to the classification of superior cultivated land, and the fertility quality is higher (in grades 1–2) in northeastern Harbin, according to the currently measured data. However, according to the data collected by Yao et al. from 10,583 sampling points in the northeast Mollisol belt, including Harbin in 2008, the soil quality in the region where the sampling points were located was generally low (at levels 7–8). Based on measures in 2021, the quality of cultivated land in the ecological sampling corridor had improved to a certain extent compared with the surrounding cultivated land.

Compared with the reference values in Table 1, we found that the collected soil samples from the cultivated land and artificial corridors along the Ashi River ecological corridor, except for the samples from land with corridors that were restored for two years, all reached the standard value of Mollisols. In contrast to the previous study [41], the ST index in the ecological corridor (recovery time > 10 years) greatly exceeded the reference value. We believe the phenomenon caused by the previous study was a large-scale soil census-type study, and the arrangement of sampling points is more inclined to the census of soil quality in the Mollisol soil zone and the arrangement is sparse. In the experiment conducted in this paper, the sampling site was smaller and the sampling point distribution accuracy was high. It is also reflected in Yuan's [53] study that the average interpolation accuracy of different soil properties caused by different scale sampling varies greatly. At the same time, this may also be related to the restoration of soil fertility in farmland and plantation belts along the Ashi River ecological corridor within a specific range, after the ecological restoration of the Ashi River ecological corridor for nearly 30 years, showing the phenomenon that the soil quality is better than the surrounding soil in the same soil belt. In Marcela's [54] and Su's [24] study, it is also supported that the restoration of the soil biodiversity through ecological corridors has a good effect on the soil health directly. It also suggests that increased local biodiversity may enhance soil nitrogen cycling and net primary production (NPP), leading to increased carbon sequestration in soils [55].

In addition, this shows the limitations of this study to a certain extent. Our next step is to collect, compare, and search for soil samples on a larger scale in the area where the Ashi River ecological corridor is located.

4.2. The Process of Establishment of Artificial Forest–River Ecological Corridor Affecting Soil Fertility

In the ecological restoration of Mollisols through forest–river ecological corridors, the change process of nutrient components in the soil first decreased and then increased. The decline time needs to be further determined. However, in the current sampling, in the first two years of restoration of the cultivated land into the ecological corridor, the soil nutrients decreased significantly, and it is worth noting that the soil EC also decreased significantly, indicating that the soil salinization degree decreased.

In the same soil zone, affected by different land-use types, soil biochemical indicators are also different [56]. This paper monitored nine biochemical indices of soil in ecological corridors with different land-use types and recovery times. In the ecological corridor, the soil is comprehensively affected by restoring the ecosystem; plants and animals are the primary sources of soil nutrients [57]. In our monitoring, we found that in the first two years of recovery, soil indicators underwent a significant decline. Decreased fertility may be due to the following factors: 1. The artificial ecological corridor is affected by the previous land use (cultivated land), and the soil fertility depends on the input of fertilizers. After being restored to an ecological corridor, the fertilizer applied will be reduced. 2. The early growth of fast-growing plantations absorbs many nutrients. 3. In the early stage of the fast-growing forest, there are few dead branches and leaves, the soil under the forest is dry, and the consumption of soil nutrients is accelerated. 4. Due to less soil cover, the soil is severely washed by rainwater in the rainy season [58]. The above reasons lead to the decline of soil fertility. The decrease in the EC index in the analyses indicated that the saline–alkaline properties of Mollisols was alleviated by rain erosion. Existing studies have shown that soil nutrients have declined to a certain extent in the early stages of the artificial secondary forest [59,60]. This indicates that ecological corridors for soil restoration should be a long-term project. Studies have shown that long-term ecosystem restoration improves soil health and the carbon storage capacity of the largest source of greenhouse gas emissions (cultivated land) [61–63]. Our monitoring found that the five changed indicators have been restored to the normal range of Mollisol values in ecological corridors with a recovery time of more than ten years, and the ST indicators have been significantly exceeded.

We believe that it is feasible to restore Mollisols by constructing an artificial ecological corridor, which is similar to the research results of Di Wang [11]. Moreover, we further confirmed that soil restoration is a process of first decreasing and then increasing. However, at present, there are few studies on the reduction period. In this study, there are few samples (six) with a recovery time of between 2 years and 10 years. At the same time, the distances from the Ashi River of these six indicators are mostly concentrated within the range of <30 m, which are greatly affected by river water rise and many uncontrollable factors. It is difficult to support the research on the decline period, which is also a limitation of this paper. In subsequent studies, the physical and chemical properties of artificial ecological corridors at various stages of Mollisol restoration will be further explored.

4.3. Unilateral Width and Recovery Time of the Best Soil Restoration Artificial Forest–River Ecological Corridor

The best soil restoration artificial forest–river ecological corridor unilateral width is 175–225 m, and recovery time is 22.7–35 years. Different protection widths and recovery times of artificial restoration of the ecological corridor have significant effects on soil ecological chemical indices [40,64]. Soil health is closely related to intra-domain ecosystem function [65].

The sampling points in the ecological corridor with less human disturbance are affected mainly by the recovery time. In addition, we conducted a multiple linear regression and evaluated the contribution of the indicators with differences in width and recovery time in the soil. Studies have shown that for SOC, the longer the recovery time of artificial secondary forests, the greater the SOC index in soil [66]. For the EC, the effect of recovery time more than the distance to the Ashi River effect is similar to Brye's study [67]. It shows that when the ecological corridor is restored in the Mollisol area, the restoration rate of its related soil eco-chemical indicators will be significantly affected by the different width and recovery time. We selected the two arrows (CEC and SOC) with the most significant contribution of distance and the two arrows (SOC and EC) with the most crucial contribution of recovery time for further analysis. We found the value of 175–225 m to be the optimal width of the unilateral corridor. We found a recovery time of 22.7–35 years to have a high degree of correlation with the model. We found the effects on the soil of distance from the ecological corridor center and recovery time similar to the results of Wang [11] and Schalkwyk [35]. Besides, we further selected the best protection width and recovery time limit of the corridor from the perspective of Mollisol restoration. It provides a high-volume, low-cost soil remediation method (ecological corridor) in areas with extensive soil damage. It gives an optimal range of unilateral width for conservation and restoration time. Moreover, with the increase of SOC content in Mollisols, our study showed that, given enough time, we could sequester more carbon in the soil of the artificial forest–river ecological corridor in the long term, which also supports Strand's [42] research.

In the process of summing up the best recovery time and width, we found that in the latter part of the model regression, the degree of correlation between the measured values and the model was reduced. It is also the basis for us to delineate the scope of influence on ecological corridors, and we only select the parts with a high degree of correlation for delineation. The one-dimensional linear model is obvious in the selected interval, but whether it is established in the case of long-distance or time sequence is worth considering. Finally, we acknowledge a limitation of this study was that the sample size of greater distance and longer time sequence was relatively small.

5. Conclusions

In this study, we explored the relationship between the stoichiometric ecological characteristics of Mollisols and the characteristics of recovery time and distance from the ecological corridor of the Ashi River. By analyzing the stoichiometric characteristics of the soil, we found significant differences in soil indicators in different land-use types and recovery times. Many soil factors were detected at the highest levels in ecological corridors rehabilitated for more than 10 years, such as ST, DMC, and TK, and at the lowest levels in ecological corridors for only two years, such as ST, EC, CEC, SOM, and SOC. Soil properties were significantly correlated with the land-use properties and recovery time. In addition, we also found that in the same land-use type, there were significant indigenous differences in the soil indicators at different locations within the ecological corridor, from the center as compared to the edge. We studied the ecological restoration process of Mollisols along a transect of the forest–river ecological corridor. Findings evidence a process in which soil nutrients first decrease, then increase, and finally reach and exceed the standard Mollisol reference value. A redundancy analysis (RDA) of the sample found that the distance from the forest–river ecological corridor was a key factor affecting EC, CEC, SOC, and SOM. After limiting the types of land use (artificial ecological corridor) and removing the samples affected by river flooding (distances from the Ashi River < 10 m), the analysis of key soil indicators showed that the corridor recovery time had a higher contribution to the EC and SOC indicators. The recommended unilateral width of the ecological corridor is 175–225 m and the restoration period is 22.7–35 years, based on the Mollisol EC and SOC indices for restoration. These results only predicted and represented soil formation in this sampling period and section.

The next step is to determine and explore the mathematical relationship between a more accurate ecological corridor width and the number of years of Mollisol restoration, and soil indicators, through a larger range and quantity of measured experiments. This conclusion is of great significance for the segmented construction, delineation, and management of ecological corridors in cities and suburbs of Mollisol areas in Northeast China at the present time and for ensuring the healthy ecological function of ecosystems in corridors. Our approach is transparent and reproducible; we believe it is more easily applicable to larger areas and provides a reliable baseline assessment for soil restoration, ecosystem restoration, and habitat suitability selection, which can help local governments develop land use planning and the design of soil restoration ecological networks.

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