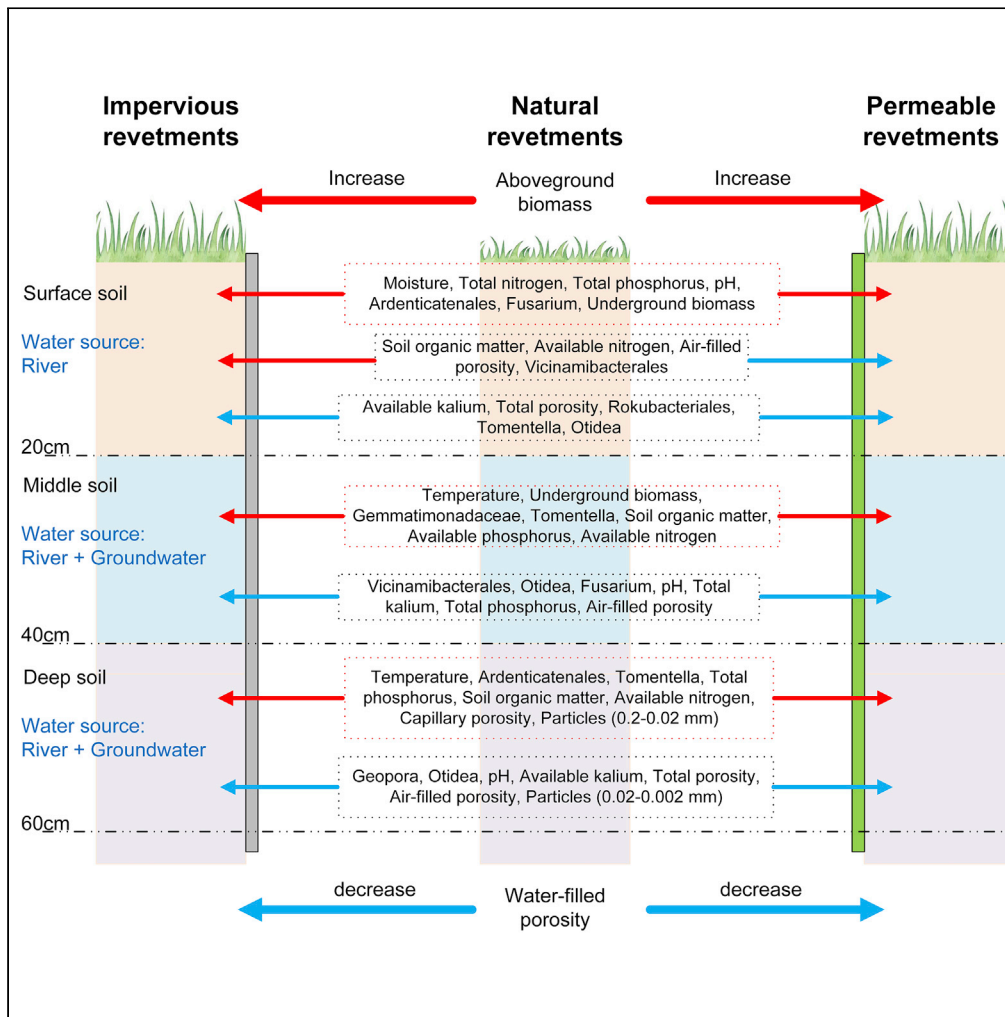


Article

Effects of revetments on soil ecosystems in the urban river-riparian interface



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Highlights

Revetments affect soil ecosystems in the urban river-riparian interface

Revetments have different effects on the properties of surface, middle and deep soil

The exchange of material and energy is variable at different revetments



Article

Effects of revetments on soil ecosystems in the urban river-riparian interface

Zihao Man,¹ Changkun Xie,¹ Ruiyuan Jiang,¹ Anze Liang,¹ Hao Wu,¹ and Shengquan Che^{1,2,*}

SUMMARY

By altering material and energy exchange between river and riparian, the city revetments have an unknown impact on the service function of river-riparian interface (RRI) ecosystems. This study analyzes the differences in natural, permeable (PR), and impervious revetment (IR). We found that the water-filled porosity of revetment increased from 20% to 100%, which coincided with an increase in soil potassium, air-filled porosity, the surface soil of moisture and organic matter (SOM), and a decrease in soil nitrogen, phosphorus nutrients, and in the middle and deep soil SOM. The changes affected the abundance of dominant bacterial and fungi genera. Compared with the PR, surface soil moisture, pH, and underground biomass were lower in IR surface soils, while surface soil SOM and middle soil moisture were higher. This research provides a development direction and theoretical basis for future urban planning and environmental governance.

INTRODUCTION

The river-riparian interfaces (RRIs) of urban rivers are the areas where river ecosystems interact with the riparian soil ecosystems and are also the primary point for the exchange of material and energy between river waters and riparian soils (Yan et al., 2019a, 2021). RRIs can improve the uptake of various nutrients from rivers to improve water quality, while also intercepting and filtering surface runoff to alleviate the eutrophication of urban rivers (Johnson and Wilby, 2015; Hénault-Ethier et al., 2017; Trauth et al., 2018).

The intensification of urbanization has led to the construction of various types of revetments at urban RRIs. Their addition is likely to change the natural material and energy exchange rates, in addition to the pathways of rivers and riparian zones, thereby leading to unnatural material-energy cycling. These dynamics then influence the evolution of soil properties and vegetation at RRIs (Xie et al., 2022), thereby altering ecosystem service functions and RRI ecological capacities (Zhu et al., 2021; Strain et al., 2022).

Revetments can be divided into three categories based on material and energy exchange (Yan et al., 2019a, 2019b, 2021) including the following: 1) natural revetments (NR) with no artificial structures between rivers and RRIs; the material or energy exchange between river ecosystems and riparian soil ecosystems is almost unimpeded, the water-filled porosity of revetment (WFPR) equal to 100; 2) impervious revetment (IR) with impervious artificial structures existing between rivers and RRIs; the material or energy exchange between river ecosystems and riparian soil ecosystems is almost completely diminished (WFPR = 0); and 3) permeable revetments (PR) with permeable artificial structures between rivers and RRIs; the material or energy exchange between river ecosystems and riparian soil ecosystems is hindered ($0 < \text{WFPR} < 100$). Thus, different types of revetments differ among systems, as do the state when the material and energy exchange between river ecosystems and RRI soil ecosystems equilibrate, and these differences directly affect water migration. Importantly, the exchange of heat, pH, and nutrients between rivers and riparian areas primarily depends on water migration.

Changes in soil moisture results in changes in the continuity of soil heat flow that then affects soil thermal conductivity, thermal resistance, and heat capacity, leading to changes in soil temperatures. Different initial soil moistures differentially affect soil thermal properties (Amaludin et al., 2016). As soil moisture decreases, soil particle distributions also decrease and adhesion between particles increases (Sun et al., 2021). Furthermore, the abundance and connectivity of soil pores that allow gas flow increases, leading

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to increased gas permeability of soils (Rodrigues et al., 2011; Deepagoda et al., 2011; Mentges et al., 2016). Soil gas permeability is an important factor in the formation of aerobic and anaerobic environments that affect the growth of vegetation and microorganisms (Tang et al., 2011). Soil water-holding capacity reflects the ability of soils to store and supply water for vegetation and microbial communities. Likewise, soil organic matter (SOM) reflects the ability of soil to store and supply nutrients for vegetation and microbial growth. In addition to soil moisture, other properties including SOM, porosity, and particle size also affect soil gas permeability (Mentges et al., 2016). Moreover, soil moisture and soil water-holding capacity are affected by soil porosity, bulk density, particle size, and arrangement (McTaggart et al., 2002; Joshi and Mohanty, 2010; Wang and Franz, 2015; Wang et al., 2017; Wu et al., 2020a, 2020b; Dong and Ochsner, 2021), while soil bulk density is also affected by soil texture and porosity. Likewise, SOM affects soil porosity, particle size, and water-holding capacity, in addition to the abundance, composition, and diversity of microbial communities via the alteration of soil structures (Gregory et al., 2009, 2015; Johnston et al., 2009). In addition, increased SOM can improve soil water-holding capacity, reduce runoff loss, and improve soil gas permeability. However, the levels and distributions of soil porosity are primarily affected by water migration (Cárdenas et al., 2010; Jin et al., 2017). Consequently, the impacts of revegetation on water and nutrient migration may cause altered gas permeability, water-holding capacity, and nutrient-supplementation capacity of soils.

Microbial community composition and function are affected by vegetation characteristics, soil temperature, pH, and the availability of water and nutrients (Fierer and Jackson, 2006; Lauber et al., 2008; Fierer et al., 2009; Vogel et al., 2009; Angel et al., 2010; Jin et al., 2010; Nemergut et al., 2011; Brockett et al., 2012; Ma et al., 2012; Waldrop et al., 2017; Ren et al., 2018; Wu et al., 2020a, 2020b; Xu et al., 2021). Some studies have also suggested that soil moisture can indirectly affect the local abundances of soil microorganisms by affecting SOM along with pH, which may also affect soil microbial community compositions (Siciliano et al., 2014; Tedersoo et al., 2014). In addition, some studies have suggested that fungi are more sensitive to vegetation characteristics, while bacterial communities are more sensitive to soil nutrient variation (Zhang et al., 2011; Yang et al., 2020). Fungi are better adapted to adsorb nitrogen and phosphorus and thus, lower soil nutrient availability may promote fungal proliferation. Bacterial communities are primarily altered by adjusted lifestyles that then modify community composition to adapt to soil nutrient levels (Zhang et al., 2016; Zhou et al., 2018). Soil microbial communities control important ecosystem processes like the cycling of carbon, nitrogen, and other nutrients, in addition to organic matter decomposition, organic matter formation, and the growth of vegetation (Marschner and Rumberger, 2004; Balsler and Firestone, 2005; Aubert et al., 2010; Hol et al., 2010). Nevertheless, the primary factors that affect vegetation growth are the availability of soil moisture and nutrients (Li et al., 2018). In addition, the litter and root exudates of vegetation can provide different types of carbon and nitrogen nutrient sources for microorganisms, further affecting the composition and structure of soil microbial communities (Kara et al., 2008). Similarly, soil microorganisms may decompose these substances, thereby indirectly altering soil properties like pH, organic matter, and nutrient ratios (Blum et al., 2000; Burton et al., 2010). Soil structure affects the distribution of vegetation roots, but roots also alter soil structures to adapt to or change soil microenvironments through direct infiltration, anchoring, water extraction, and compound seepage into rhizospheres (Rich and Watt, 2013; Jin et al., 2013, 2014; Bengough et al., 2016; Oburger and Schmidt, 2016; Pierret et al., 2016; Popova et al., 2016). Concomitantly, roots can also have long-term effects on soil structures by providing SOM (Bardgett et al., 2014; Lange et al., 2015) that can act as nutrients for plants and microorganisms, thereby promoting plant and microbial growth (Murphy, 2015). However, the SOM decomposition rate and the availability of nutrients are primarily related to the characteristics of SOM and microbial communities. For example, the availability of nitrogen from the decomposition of organic matter primarily depends on the carbon-nitrogen ratio of organic matter. If the nitrogen content in the organic matter is low, soil microorganisms can absorb more nitrogen than nitrogen that is released into the soil (Murphy, 2015). In addition, the availability of soil moisture and nutrients are affected by soil porosity, water-holding capacity, pH, and depth (Gonçalves and Carlyle, 1994; Rodrigo et al., 1997; Leirós et al., 1999). Conversely, the combination of soil roots, mycelia, and particles can stabilize soil aggregates, jointly determining the soil porosity, particle size, and other soil properties (Murphy, 2015), consequently affecting water-holding capacity (Auge et al., 2001).

Based on the above observations, changing revegetation types should affect various soil properties at RRIs via complex interactions between physical, chemical, and biological properties of soils that together determine changes in RRI ecosystem service functions. Soil properties and vegetation at RRIs evolve in different

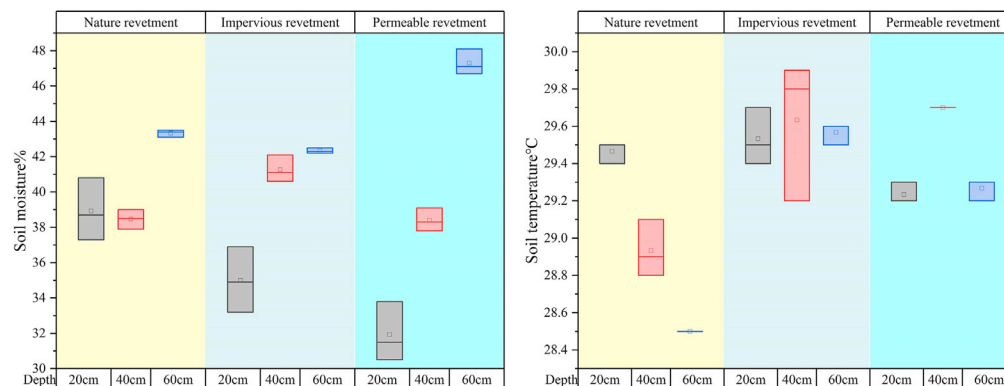


Figure 1. Distribution of soil moisture and temperature among soil layers

directions over time, leading to significant changes in their ecosystem services like water purification and runoff pollution filtering that are likely to become important targets for future environmental governance. However, few studies have evaluated the impact of urban revetment types on the physical, chemical, and biological properties of riparian soils, and few studies have primarily focused on indoor control experiments to assess the impacts of revetment types on a single riparian soil parameter. Moreover, even though RRIs of urban rivers play important roles in the river and riparian conditions, they have received less attention. Rather, many studies have included RRIs within riparian systems, causing many of their unique functions to be ignored.

In this study, the hypothesis that urban revetment affects soil ecosystems at RRIs was evaluated. Specifically, we hypothesized that revetment affects water migration between rivers and soils at RRIs, in addition to affecting soil moisture, nutrient concentrations, temperatures, and pH at RRIs. We further hypothesized that soil pH, moisture, nutrient concentrations, temperatures, and other soil physical, chemical, and biological properties, in addition to gas permeability, water-holding capacity, and nutrient-supplying power interact with each other, thereby determining the states and functions of RRI soil ecosystems.

RESULTS

Soil physical properties of RRIs from different revetment types

Comparison of 0–60 cm soil profiles of the NR, IR, and PR sites indicated that greater soil moisture was measured with greater depth (Figure 1). The NR site exhibited the highest surface soil (SS) moisture that was 11.24 and 21.92% higher than at the IR and PR sites, respectively. The middle soil (MS) moisture from the IR site was higher than that in the NR and PR sites, while the deep soil (DS) moisture of the PR site was highest. Lower soil temperatures were observed with depth in the 0–60 cm layers of NR soils. The MS layer of the PR layer had the highest temperature, while the SS and DS layers exhibited lower temperatures.

Soil bulk density (BD) decreased with depth across the 0–60 cm soil layers (Figure 2). The BD of the SS at IR was 20.36%, representing an 11.23% larger value than in the NR and PR sites. The BD of the MS layer at the PR site was 9.12%, representing an 11.93% larger value than in the NR and IR sites. The BD of the DS layer at the NR site was 5.28%, representing a 2.24% larger value than observed at the IR and PR sites. Total porosity (Tp) and capillary porosity (CP) increased with depth at the NR, IR, and PR sites. In contrast, air-filled porosity (AFP) did not exhibit clear vertical distribution trends. The CP of the SS layer at NR was 73.59%, a 4.31% larger value than observed at the IR and PR sites. The CP of the MS layer at IR was 7.31%, representing a 24.79% larger than observed for the NR and PR sites. The CP of the DS layer at IR was 11.74%, and an 8.70% larger value than that observed for NR and PR. AFP differences were very large among different revetment types and soil depths.

The distributions of soil particles in the <0.002 mm fraction and soil particles in the 0.2–2 mm fraction were irregular (Figure 2). Very few soil particles were observed in the 0.2–2 mm range and were only detected in the MS and DS layers of the PR site. The specific gravity of surface soil particles in the 0.002–0.02 mm fraction of PR soils was 0.36%, representing 10.32% larger values than at NR and IR. The specific gravities of the

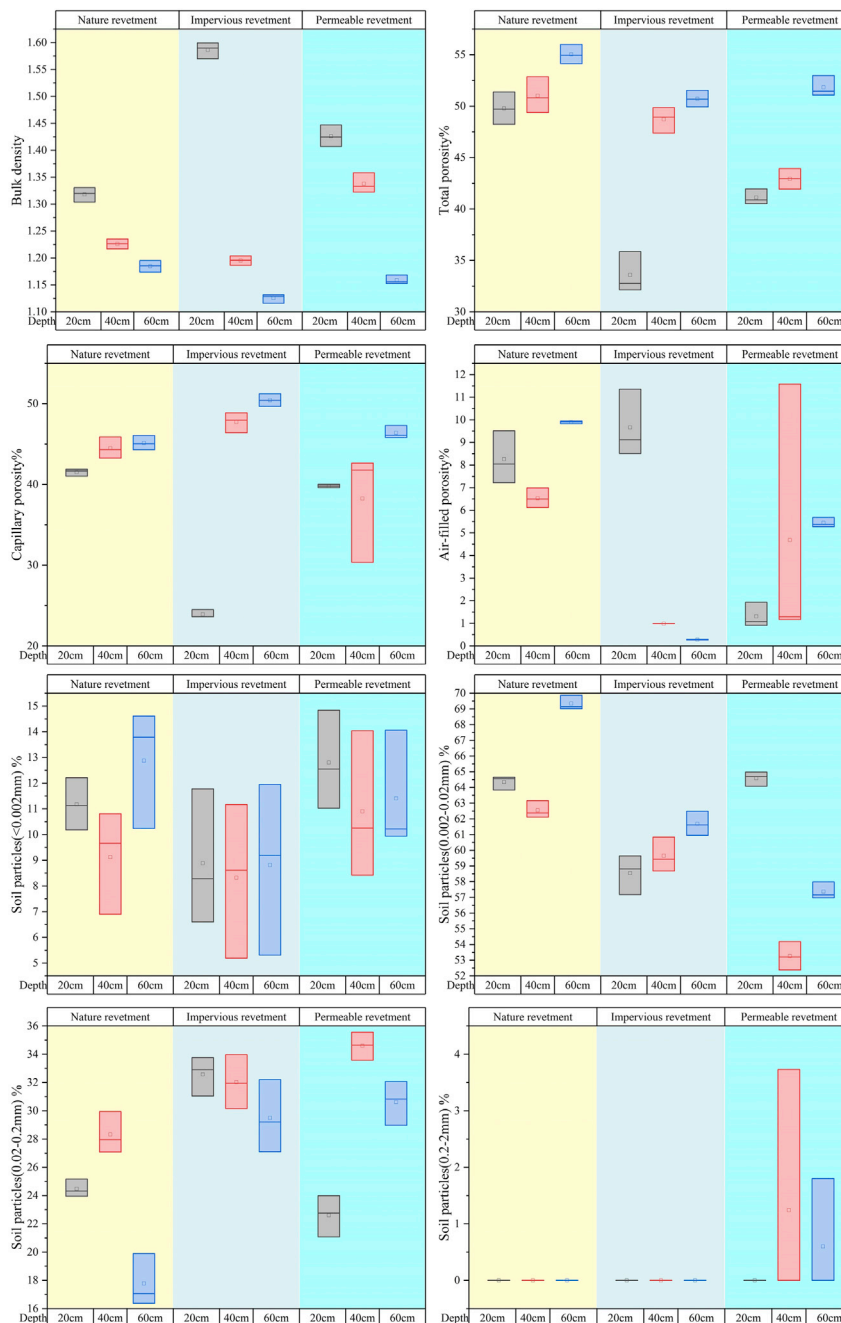


Figure 2. Distribution of bulk density, porosity, and particle diameter among soil layers

middle and deep soil particles of the 0.002–0.02 mm fraction at NR were larger than at IR and PR. Concomitantly, the proportion of soil particles in the 0.02–0.2 mm fraction was largest in the MS layer of the NR and PR sites. The specific gravity of surface soil particles of the 0.02–0.2 mm fraction at IR was 33.05%, representing a 44.05% larger value than at the NR and PR sites. Lastly, the specific gravity of surface soil particles in the 0.02–0.2 mm fraction at PR was 22.12%, representing an 8.03% larger value than at NR and IR.

Soil chemical properties of river-riparian interfaces in different revetment type sites

pH increased with soil depth at the NR site (Figure 3). At the IR and PR sites, pH was highest in the SS layers, but lowest in the MS layers. The surface soil pH at the NR site was lower than in IR and PR soils,

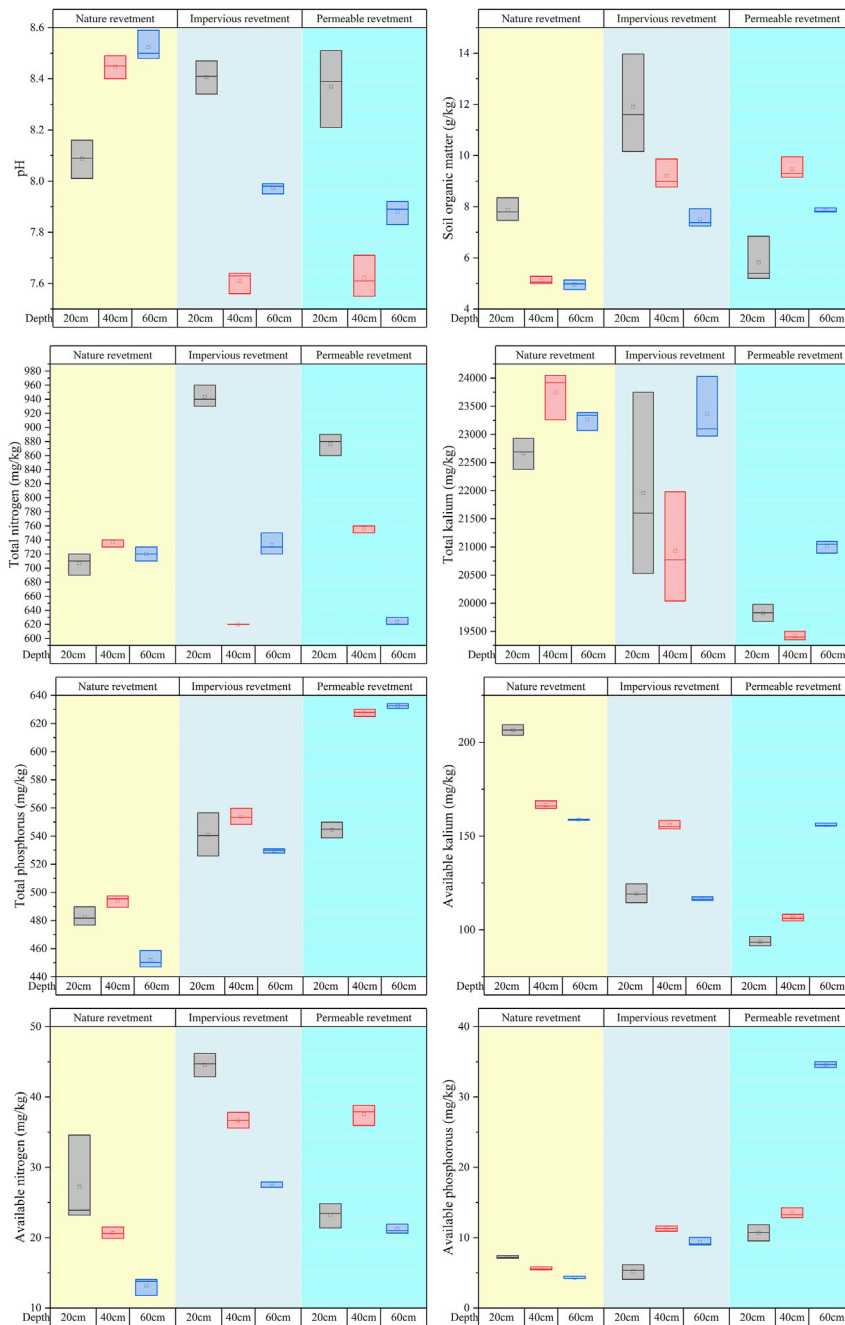


Figure 3. Distribution of soil pH, soil organic matter, total nitrogen, total phosphorus, total kalium, available phosphorus, available nitrogen, and available kalium

while the pH in the middle and deep soils of NR was larger than at IR and PR. Furthermore, SOM decreased with depth at the NR and IR sites. The surface SOM in IR was 51.29%, representing a 104.86% larger value than in the NR and PR sites. The middle layer SOM value at PR was 85.38 and 2.83% larger than at the NR and IR sites, respectively, while the deep SOM at PR was 58.29 and 4.54% larger than at the NR and IR sites.

The soil total nitrogen (TN) of SS and DS layers at IR was larger than at the NR and PR sites, while the TN of the MS layer at PR was 2.71 and 22.04% larger than at the NR and IR sites. Total kalium (TK) in the 0–60 cm

soils of NR was greater than at PR. Total phosphorus (TP) in the MS layer was the largest at the NR and IR sites, while TP in the DS layer was the lowest. However, TP increased with soil depth at the PR site.

Soil available kalium (AK) and available phosphorus (AP) decreased with depth at the NR site, while they both increased with soil depth at the PR site. AK and AP were largest in the MS layer at the IR site. The AP values were higher in PR soils than in NR and IR soils. Soil available nitrogen (AN) increased with depth in NR and IR soils. The AN of the SS layer in IR soils was 63.75 and 92.06% larger than in NR and PR soils, while the AN of the MS layer at PR was 81.75 and 2.38% larger than in NR and IR soils. In addition, the AN of DS layers at IR was 109.36 and 30.54% larger in NR and PR soils.

Soil bacterial and fungal communities among river-riparian interface soils with different revetment types

The dominant bacterial phyla in the three revetment types were *Acidobacteriota*, *Chloroflexi*, *Proteobacteria*, and *Methylomirabilota*, while the dominant fungal phyla were *Basidiomycota* and *Ascomycota* (Figures 4 and 5). The dominant bacterial orders were *Vicinamibacterales*, *Rokubacterales*, *Ardenticatenales*, and *Gemmatimonadaceae* (Figures 6A, 7A, and 8A). The *Vicinamibacterales* were most abundant in the SS and DS layers of the IR soils, but most abundant in the MS layer of NR soils. The *Rokubacterales* abundances in the SS layer of the NR site were 26.33 and 41.42% larger than in the IR and PR soils, but 44.88 and 53.17% larger in IR soils than in NR and PR soils. The *Rokubacterales* abundances in the DS layer of the IR site were 136.67 and 216.96% larger than in that layer of the NR and PR soils. *Ardenticatenales* abundances in PR soils were always larger than in NR and IR soils, while *Gemmatimonadaceae* abundances in IR soils were always larger than in NR and PR soils.

The dominant fungal genera were *Tomentella*, *Geopora*, *Otidea*, and *Fusarium* (Figures 6B, 7B, and 8B). *Tomentella* abundances in the SS layer of NR were 51.57 and 104.8% larger than in the IR and PR soils, respectively, while their abundances in the MS layer of PR soils were 763.92 and 70.45% larger than in NR and IR soils, respectively. *Tomentella* abundances in the DS layer of IR soils were 136.93 and 11.94% larger than in NR and PR soils. In addition, *Geopora* and *Otidea* abundances of NR soils were larger than in IR and PR soils. *Fusarium* abundances increased with soil depth at the NR site, while their abundances were highest in the DS layer of IR and PR soils, but lowest in their MS layers.

Herb biomass among river-riparian interface soils with different revetment types

Vegetation roots in the SS layer were larger than in the MS layers for soils at all three revetment types (Figure 9). The underground biomass (UB) in the SS and MS layers at the PR site was larger than in NR and IR soils. In addition, the UB in the SS layer in PR soils were 61.4 and 27.74% larger than in NR and IR soils, while the UB in the MS layer of PR soils were 85.61 and 25.32% larger than in NR and IR soils. Few herb roots were observed in DS soils, so they were ignored for these analyses. The aboveground biomass (AB) at the IR and PR sites were similar, while the AB in NR soils was smaller, at approximately 0.42 times that observed in IR and PR soils.

DISCUSSION

Effects of revetments on surface soils in river-riparian interfaces

In this study, the hypothesis of direct and indirect effects of revetment types on soil ecosystems at RRI was evaluated. In addition, elevation differences between river water levels and groundwater levels were found to be the primary driver of differences in soil moisture at different soil depths thereby requiring the consideration of soil depth within soil ecosystems at RRI. The hypothesis comprises five components that were used to evaluate a distributed structural equation model for the SS layer (Figure 10), mainly including: (1) The direct effect of revetments on soil moisture, temperature, pH, and nutrients (Figure 10A); (2) The interaction of soil moisture, temperature, pH and nutrients with soil structure (Figure 10B), soil microorganisms and plants (Figure 10E); (3) The interaction of soil organic matter with soil microorganisms and plants (Figure 10D); (4) The effect of soil organic matter on soil structure (Figure 10C). A significant positive correlation was observed between soil moisture and WFPR in the SS layer, indicating that the main source of surface soil moisture derives from the river. NR soils exhibited the largest WFPR, and the amount of river replenishing the SS was the largest (Figure 1). WFPR was reduced from 100% to 20% and surface soil moisture also decreased. Greater WFPR values indicated additional river replenishment of RRI surface soils, but when river water levels decreased below the SS, surface soil water losses increased. Two primary reasons explain

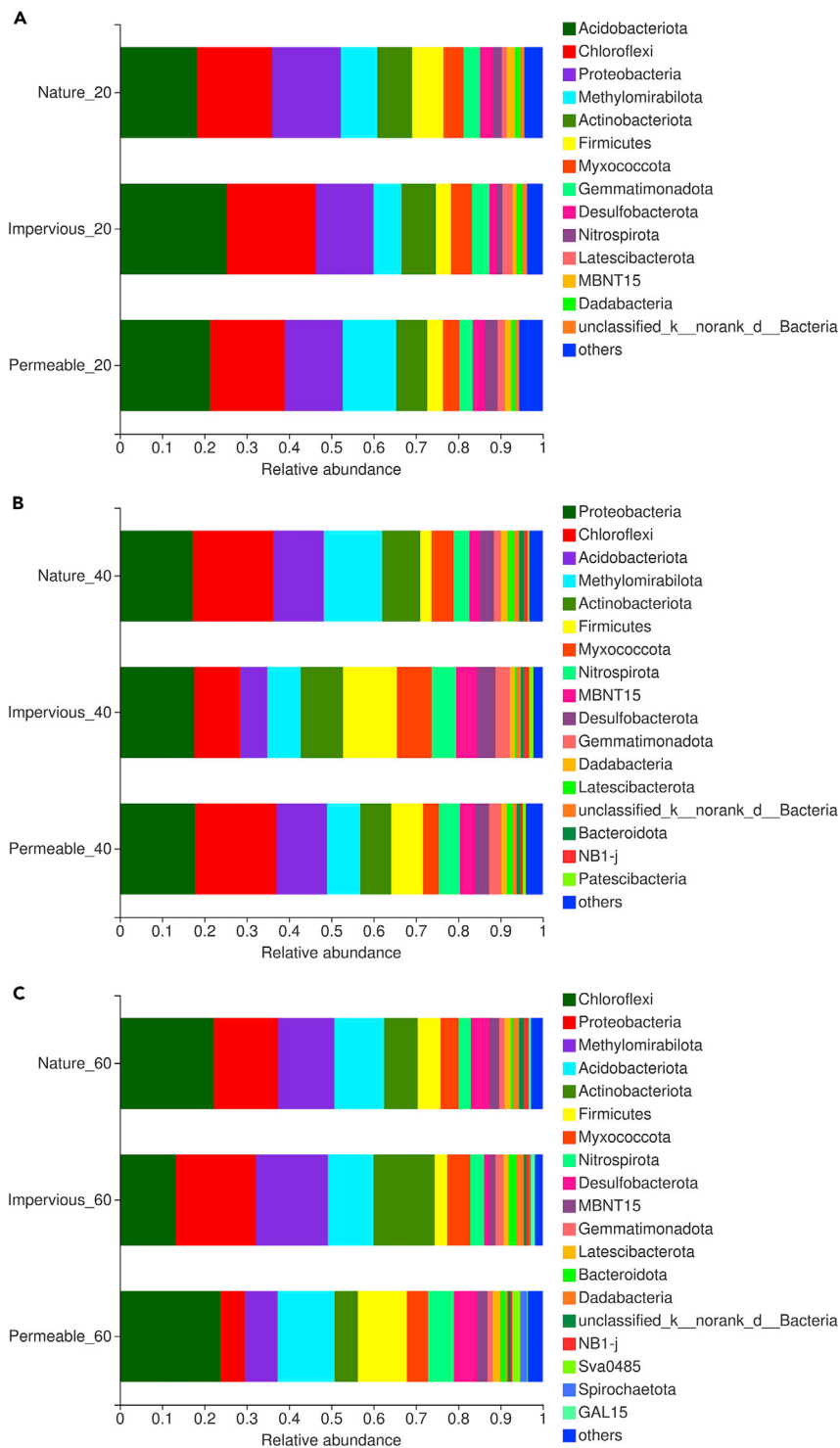


Figure 4. Abundances and variation in soil bacterial phyla
Bacterial compositions are shown for (A) surface soils, (B) middle soils, and (C) deep soil sites.

why the surface soil moisture at IR was greater than at PR. First, the mechanisms by which the river replenishes surface soil moisture differed. Specifically, the river laterally penetrated through the revetment to replenish the surface soil moisture at PR and NR, while the river replenished surface soil moisture at IR

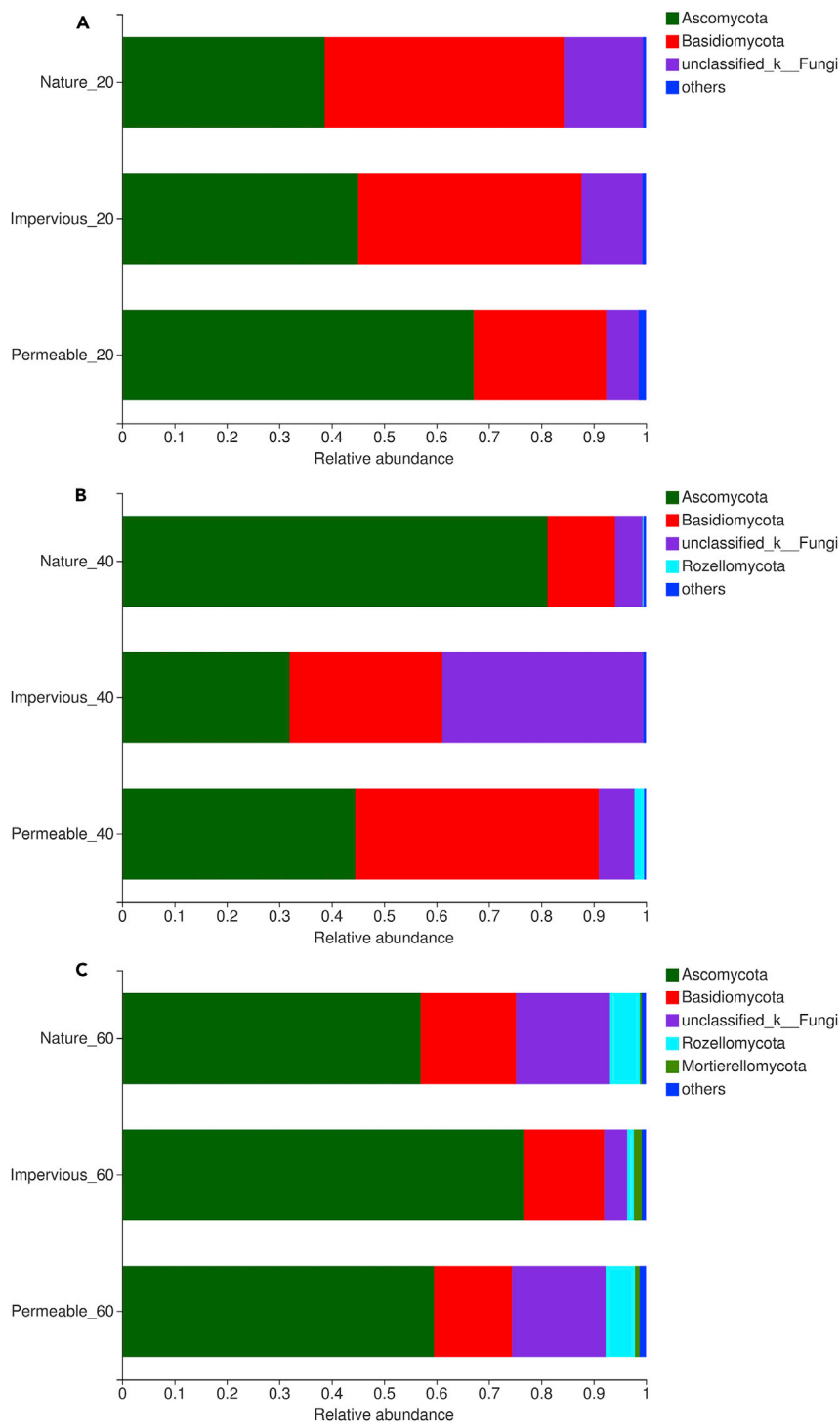


Figure 5. Abundances and variation in soil fungal phyla, and fungal compositions are shown for (A) surface soils, (B) middle soils, and (C) deep soils sites

through the submerged revetment. Second, the mechanisms underlying surface soil water loss differed. Surface soil water loss at IR primarily occurred through evaporation, while surface soil water at NR and PR could be lost through revetment in addition to evaporation. Therefore, increased WFPR could increase river water flows into the SS of RRI, in addition to increasing water loss. When the WFPR was 20%, the loss

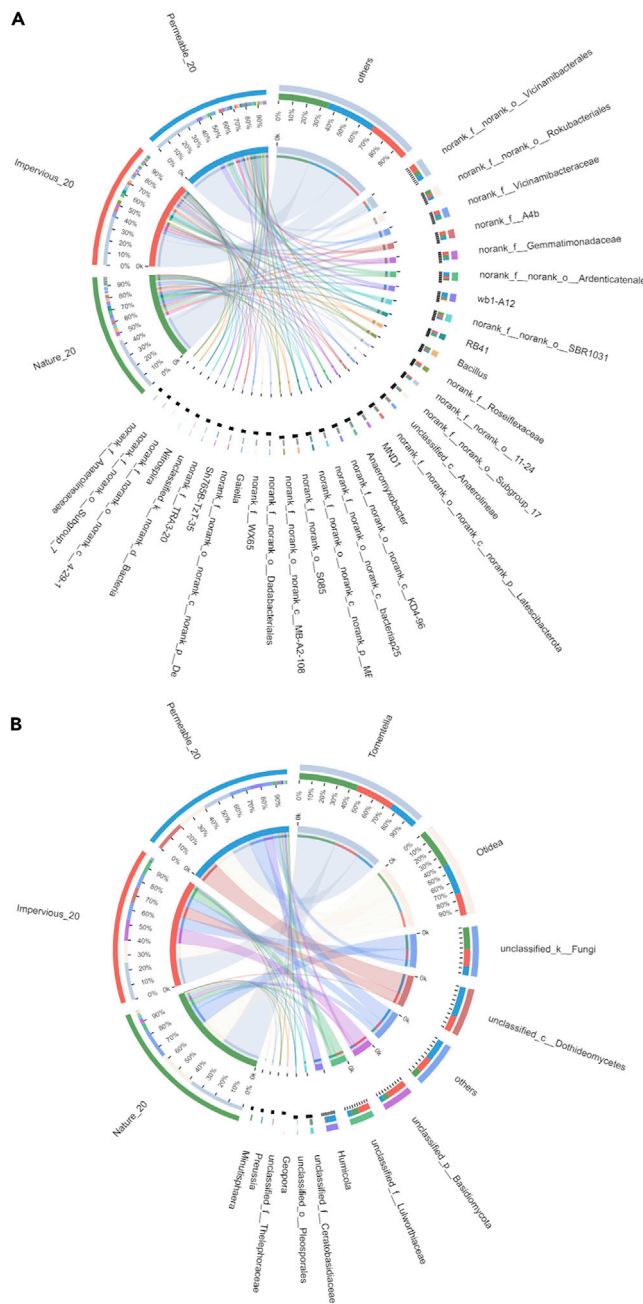


Figure 6. Abundances and variation of soil (A) bacterial and (B) fungal genera in surface soils sites

was greater than replenishment. Furthermore, WFPR did not significantly affect surface soil temperatures (Figure 10A). Although there was heat exchange between the river and SS soils, the main sources of heat in SS layers were radiation, decomposition of organic matter, and air. This also explained why soil moisture and temperatures at RRI did not affect each other in most natural environments.

A negative correlation was observed between soil moisture and BD (Figure 10B), consistent with the results from many previous experimental studies and hydrological models (Gong et al., 2003; Dong et al., 2021). Nevertheless, the negative correlation between soil moisture and BD in surface soils in the distributed structural equation model was not significant. In contrast, a significant positive correlation was observed between soil moisture and AFP, indicating that when the river was the primary source of surface soil

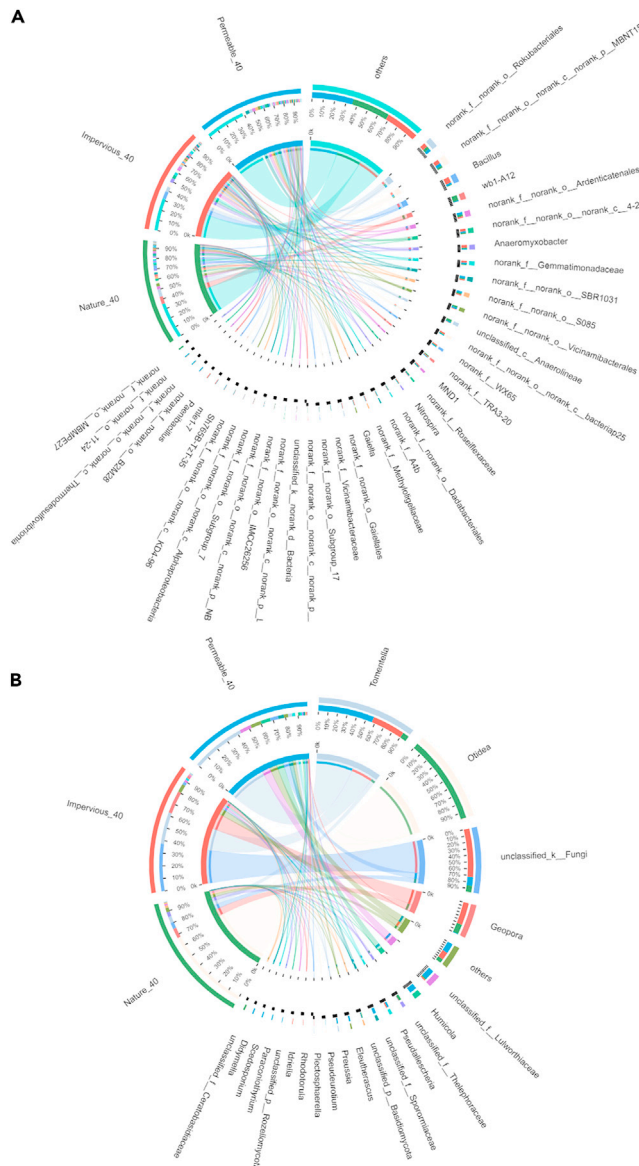


Figure 7. Abundances and variation of soil (A) bacterial and (B) fungal genera in middle soils sites

moisture, it was difficult to saturate surface soil moisture for a long time, and its moisture primarily depended on AFP used for water migration. The AFP in NR and PR soils was greater than in IR soils (Figure 2), further confirming the importance of AFP toward surface soil moisture at RRI. Moreover, these results indicated that revetment type could slowly guide changes in AFP of SS during water migration. No significant correlations were observed between the four diameters of soil particles and surface soil moisture, indicating that although soil texture was an important factor for determining soil water-holding capacity (McTaggart et al., 2002; Joshi and Mohanty, 2010; Dong and Ochsner, 2021), soil particle arrangement had a greater impact on water-holding capacity than particle diameter.

A significant negative correlation was observed between SOM and surface soil particles in the <0.002 mm fraction (Figure 10C), along with a significant positive correlation between SOM and surface soil particles in the 0.02–0.2 mm range. This indicated that the strong adhesive force of SOM (Ni and Pignatello, 2018) promoted the transformation of soil particles in the <0.02 mm fraction to soil particles in the 0.02–0.2 mm fraction, suggesting the gradual transformation of tiny particles into medium-sized aggregates. In addition, when WFPR increased from 20% to 100%, the SOM and AFP of the SS layers increased (Figure 1).

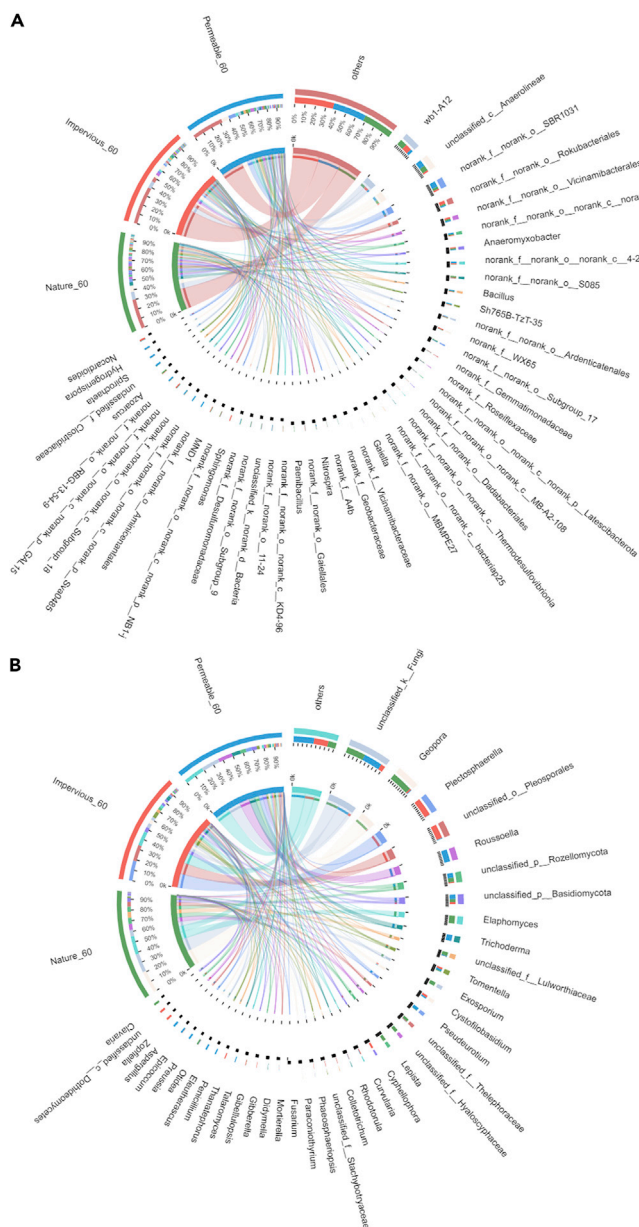


Figure 8. Abundances and variation of soil (A) bacterial and (B) fungal genera in deep soils sites

This indicated that when SOM promoted the aggregation of tiny aggregates, it significantly increased the AFP of SS soils, thereby further increasing SS soil moisture. In addition, the results of this study showed that the relationship between SOM and vegetation biomass was not significant for SS soils (Figure 10D); however, other studies have shown (Eskelinen et al., 2009; Tsioubri et al., 2020) that SOM can enhance plant respiration and increase cell membrane permeability, thereby improving the ability of plants to absorb nutrients, accelerating cell division, and enhancing plant root growth. Thus, SOM is not the primary factor limiting vegetation growth at RRI. Moreover, the influence of soil temperature on vegetation biomass at RRI was not significant, while soil moisture was significantly negatively correlated with vegetation biomass. Consequently, vegetation roots in SS soils did not lack the heat or water needed for growth. In contrast, soil moisture was too high, leading to poor soil gas permeability that may inhibit the growth of vegetation roots in SS soils. The correlations between vegetation biomass with AN and AK were not significant in SS soils, while the UB in SS soils was significantly positively correlated with AP. These results indicated that the nutrient availability in the SS soils was sufficient for vegetation growth. Concomitantly,

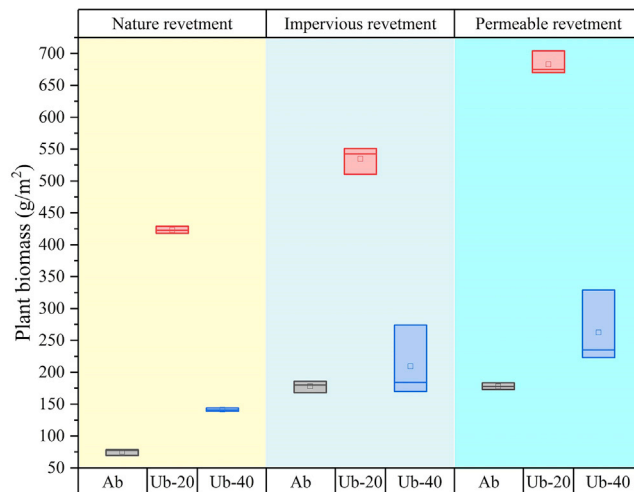


Figure 9. Distribution of aboveground and underground vegetation biomass

Ab: aboveground biomass; Ub-20: underground biomass in the surface soil layer; Ub-40: underground biomass in the middle soil layer.

soil pH was significantly and strongly positively correlated with vegetation biomass. The river pH was weakly acidic, while the pH of SS soils was weakly alkaline. This further suggested that reducing the amount of river supply to surface soil moisture could enhance gas permeability in the SS layer and improve SS soil pH, which would be beneficial to vegetation growth.

pH was significantly and negatively correlated with the abundances of *Rokubacteriales*, *Tomentella*, *Geopora*, and *Otidea* in SS soils (Figure 10E), but was significantly and positively correlated with the abundances of *Ardenticatenales* and *Fusarium* in SS soils. Surface soil moisture was significantly and positively correlated with the abundances of *Rokubacteriales*, *Gemmatimonadaceae*, *Tomentella*, and *Geopora*, but significantly and negatively correlated with the abundances of *Ardenticatenales* and *Fusarium*. Thus, the abundances of *Rokubacteriales*, *Tomentella*, and *Geopora* may be more promoted in environments with greater water, hypoxia, and weak acidity, while *Ardenticatenales* and *Fusarium* growth may be more promoted in environments with less water, aerobic conditions, and weak alkalinity. However, the surface soil moisture and pH of soils were affected by the river and thus, the abundances and distributions of these microorganisms may be affected by seasonal and hydrological changes. *Gemmatimonadaceae* abundances were significantly and positively correlated with temperature, while SOM was significantly and positively correlated with *Vicinamibacteriales* and *Gemmatimonadaceae* abundances. Thus, *Gemmatimonadaceae* activity may be closely associated with environments with high moisture, high temperature, and high SOM, while *Vicinamibacteriales* activity is associated with the decomposition or synthesis of organic matter. *Vicinamibacteriales* abundances were significantly and positively correlated with TN and AN in SS soils (Figure 10E) but were significantly and negatively correlated with AP in SS soils. *Fusarium* abundances were significantly and positively correlated with TN and TP, but significantly and negatively correlated with AK. Thus, synergistic effects may exist between *Ardenticatenales* and vegetation, while *Ardenticatenales* and *Fusarium* may affect TN, TP, TK, and AK through the synthesis or consumption of available soil nutrients.

Effects of revetments on river-riparian interface middle layer soils

WFPR was significantly and negatively correlated with middle soil layer temperature and negatively correlated with soil moisture, albeit not significantly (Figure 11A). These results were consistent with a mechanism whereby the replenishment sources of middle soil moisture are rivers and groundwaters. The middle soil layer moisture in PR soils was similar to that in NR soils, but the middle soil layer moisture in IR soils was larger (Figure 1). Thus, the river replenishes middle soil layer moisture, but when river water levels were low, moisture from middle soil layers also replenished the river and the amount of river water replenishing middle soil moisture was less than the amount of soil loss. Therefore, river and groundwater jointly replenished middle soil moisture in the IR soils, while middle layer soil moisture did not replenish the river. The middle layer soil moisture in IR soils was larger than in the NR and PR soils. Concomitantly, the loss of heat was also an important characteristic of MS layers.

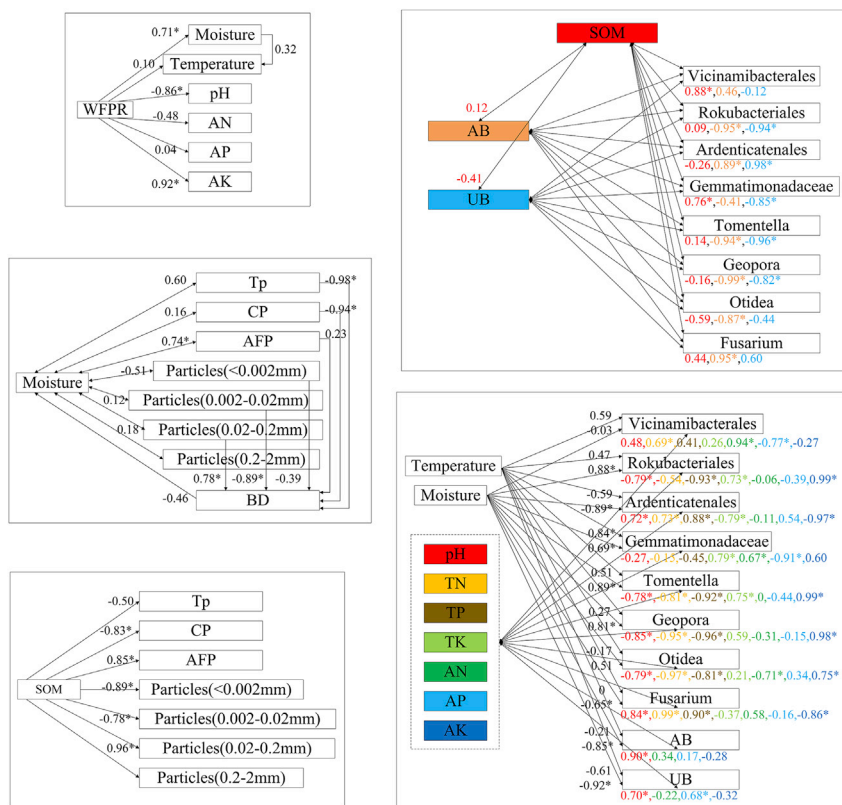


Figure 10. Distributed structural equation model for surface soils

Number color corresponds to the color of environmental factors, and * indicates that the correlation coefficient was statistically significant at the $p = 0.05$ level.

The moisture and BD in MS soils were significantly negatively correlated in contrast to SS soils (Figure 11B), indicating that hydrological models used to measure soil moisture by parameters like BD should also consider soil depth. Furthermore, middle soil moisture was significantly and positively correlated with Tp and AFP. Thus, changes in the source of replenishment led to changes in factors that determine middle soil moisture. When WFPR increased from 20% to 100%, Tp and AFP increased as well, while the middle soil layer moisture slightly changed (Figure 2). These results further indicated that Tp determined the water storage capacity of the soil, while AFP determined the ability of a river to replenish soil water and soil water loss. The relationship between soil particle size fractions and moisture was not significant for MS soils, consistent with the results for SS layers.

A significant negative correlation was observed between SOM and soil particles in the <0.002 mm fraction of MS layers (Figure 11C), in addition to a significant positive correlation between SOM and soil particles in the 0.02–0.2 mm fraction of MS soils. This indicated that SOM also promoted the transformation of soil particles in the <0.02 mm and 0.02–0.2 mm size fractions in MS soils, causing the tiny aggregates in soils to gradually transform into medium aggregates, while increased SOM significantly reduced the Tp of the MS layer. Furthermore, middle soil temperature, SOM, AN, and AP were significantly positively correlated with vegetation biomass, while soil pH was significantly negatively correlated with vegetation biomass, although the relationship between soil moisture and vegetation biomass was not significant. Thus, vegetation roots did not lack the water needed for growth in MS soils, but the requirements for temperature, SOM, and nutrients in this layer were greater.

pH was significantly positively correlated with the abundances of *Vicinamibacterales*, *Otidea*, and *Fusarium*, but significantly negatively correlated with the abundances of *Gemmatimonadaceae* and *Tomentella* in MS layers, in contrast to SS layers (Figure 11E). Middle layer moisture was significantly and positively correlated with the abundances of *Gemmatimonadaceae*, but significantly and negatively correlated

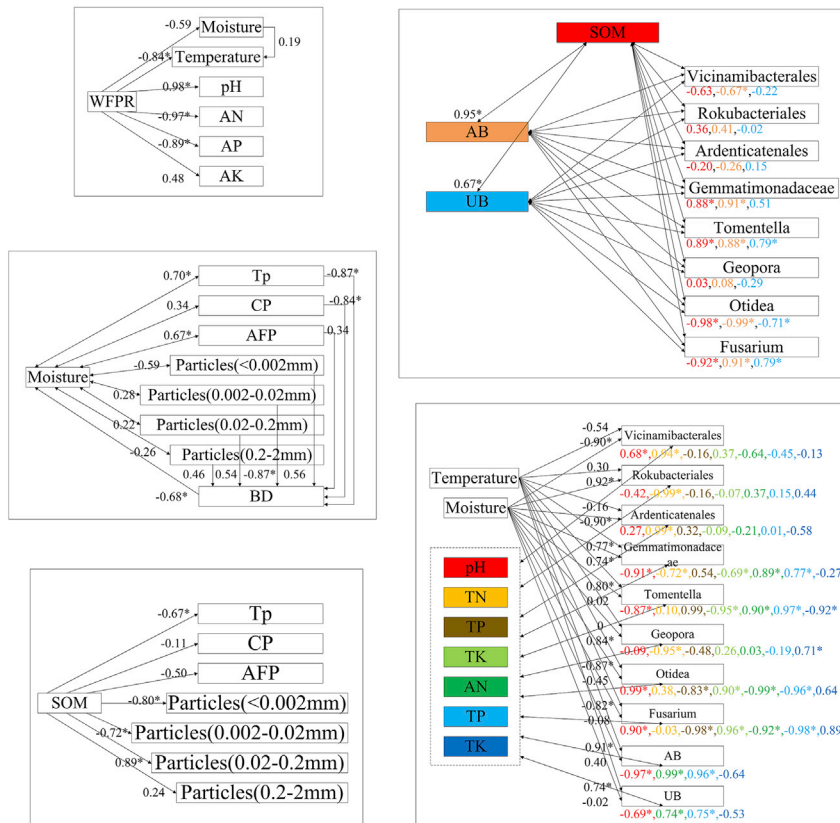


Figure 11. Distributed structural equation model of middle soils

Number color corresponds to the color of the environmental factors, while * indicates that the correlation coefficient is statistically significant at the $p = 0.05$ level.

with *Vicinamibacteriales* and *Ardenticatenales* abundances. Thus, the abundances of *Tomentella* and *Fusarium* may be more affected by MS layer pH, while *Gemmatimonadaceae* may be more affected by middle layer soil moisture. Middle layer soil temperatures were significantly and positively correlated with *Gemmatimonadaceae* and *Tomentella* abundances, but significantly negatively correlated with *Otidea* and *Fusarium* abundances. SOM was significantly and positively correlated with *Gemmatimonadaceae* and *Tomentella* abundances, but significantly and negatively correlated with *Otidea* and *Fusarium* abundances in MS soils. These results again suggest that *Gemmatimonadaceae* growth may be closely related to environments with high moisture levels, high temperatures, and high SOM levels, while *Tomentella* abundances may be closely associated with weakly acidic environments and that exhibit high moisture. In addition, *Gemmatimonadaceae* abundances were significantly and negatively correlated with TN and TK, but significantly and positively correlated with AN and AP (Figure 11E). *Tomentella* abundances were significantly negatively correlated with AN, AK, and vegetation biomass, but significantly negatively correlated with TK and AK. *Geopora* abundances were also significantly negatively correlated with TN, but significantly positively correlated with AK. *Otidea* abundances were significantly negatively correlated with TP, AN, AP, and vegetation biomass, but significantly positively correlated with TK. Lastly, *Fusarium* abundances were significantly negatively correlated with TP, AN, and AP, but significantly positively correlated with TK, AK, and vegetation biomass. These results suggest that *Gemmatimonadaceae*, *Tomentella*, *Geopora*, *Otidea*, and *Fusarium* affect vegetation growth by altering nutrient concentrations and availability in MS soils. In particular, *Fusarium* is the main taxa involved in influencing vegetation biomass in MS soils.

Effects of revegetations on deep river-riparian interface soils

WFPR was significantly negatively correlated with soil temperature but did not exhibit any correlation with moisture (Figure 12A). Thus, water exchange changes with depth, but this change is not only related to depth but is also closely related to groundwater and river water levels. In DS soils, variation in soil moisture

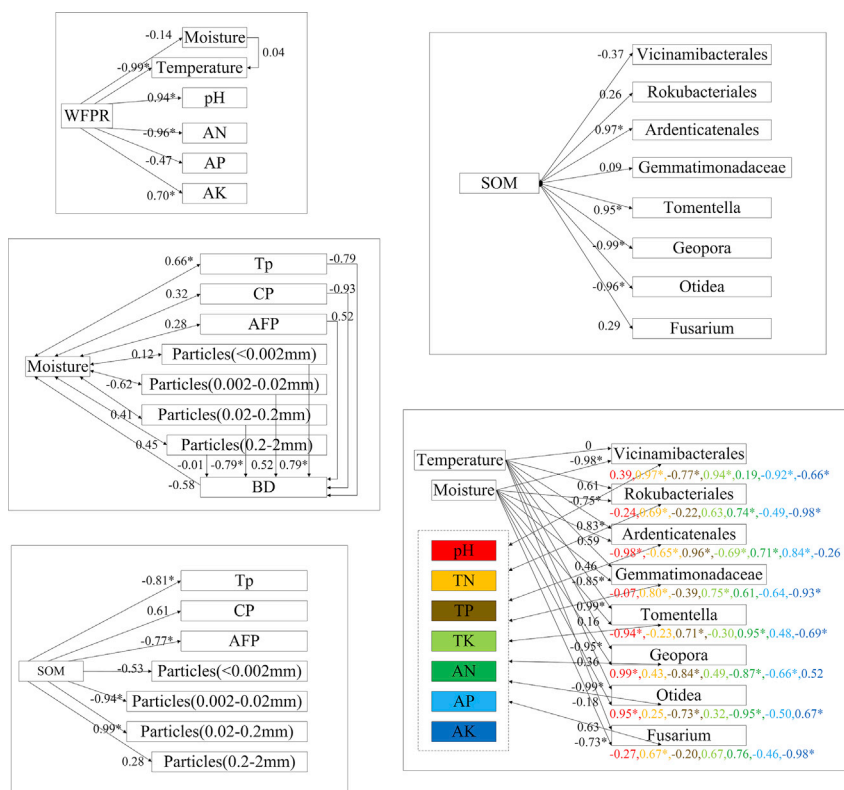


Figure 12. Distributed structural equation model of deep soils

Number color corresponds to the color of environmental factors and * indicates that the correlation coefficient is statistically significant at the $p = 0.05$ level.

is minor (Figure 1), because the water levels of groundwaters and rivers are usually not lower than the 60 cm soil layer. Furthermore, changes in BD, Tp, CP, and AFP in DS were also small (Figure 2). BD was significantly negatively correlated with moisture, while moisture exhibited a weakly significant positive correlation with Tp. Thus, soil moisture primarily depends on the size of the space that can be filled with moisture in DS soils, but this does not mean that greater Tp in DS soils will lead to greater moisture. Surface soil moisture is usually not saturated, while middle soil moisture is occasionally saturated, and deep soil moisture is always saturated. Consequently, gas in DS also competes for space, while soil temperature and moisture are completely irrelevant. The deep soil temperature was highest in IR soils but lowest in NR soils.

Interestingly, BD and moisture exhibited an insignificant weak correlation (Figure 12B). Although BD and moisture were always negatively correlated in 0–60 cm soils, the correlation between the two is only significant for MS soils. This observation may warrant future hydrological models to include weight assignments for parameters. Concomitantly, a significant negative correlation was observed between SOM and soil particles in the <0.002 mm fraction in DS soils, while a significant positive correlation was observed between SOM and soil particles in the 0.02–0.2 mm fraction of DS soils. Thus, even if water fills almost all of the DS soils, SOM still promotes the transformation of soil particles in the <0.02 mm and 0.02–0.2 mm fractions, causing the tiny soil aggregates to gradually transform into medium-sized aggregates.

In contrast to SS and MS soils, deep soil pH was significantly and positively correlated with *Geopora* and *Otidea* abundances, but significantly negatively correlated with *Ardenticatenales* and *Tomentella* abundances. Thus, *Tomentella* may always primarily associate with weakly acidic environments, while pH may not be the primary factor influencing the distribution of *Geopora*, *Ardenticatenales*, and *Otidea* in DS soils. Deep soil moisture was significantly negatively correlated with the abundances of *Vicinamibacteriales*, *Rokubacteriales*, *Gemmatimonadaceae*, and *Fusarium*. These results suggested that the very high soil moisture in deep soils may inhibit the growth of some microorganisms. SOM was significantly positively correlated with *Ardenticatenales* and *Tomentella* abundances in DS soils, but significantly negatively

correlated with *Geopora* and *Otidea* abundance in DS soils. The correlations between *Toментella*, *Otidea*, and SOM in all soil layers were consistent. Thus, SOM may be the primary factor affecting the growth of *Toментella* and *Otidea*. Additionally, *Toментella* abundances were significantly positively correlated with TP and AN, but significantly negatively correlated with AK (Figure 12E). *Geopora* abundances were significantly negatively correlated with TP, AN, and AP, while *Otidea* abundances were significantly positively correlated with AK and significantly correlated with TP and AN. These results were consistent with those of the MS soils, indicating minimal differences in the microbial community structures between MS and DS soil layers.

Conclusions

The results from this study indicated that different revegetations led to differences in the exchange of material and energy between RRI soil ecosystems and river ecosystems. Three different revegetations were constructed in the same river section and after 10 years of natural evolution, the RRI soil ecosystems exhibited obvious differences. In the surface soils (0–20 cm), the river was the primary source of soil moisture, and the primary factor that determined surface soil moisture was AFP. When WFPR increased from 20% to 100%, surface soil moisture increased by 21.92%, SOM increased by 35.41%, AFP increased by 5.32 times, UB decreased by 61.4%, and pH decreased by 3.5%. These changes coincided with increases in the abundances of *Rokubacteriales*, *Toментella*, *Geopora*, *Otidea*, *Vicinamibacteriales*, and *Gemmatimonadaceae*, along with TK and AK increased. Furthermore, *Ardenticatenales* and *Fusarium* abundances decreased, as did TN and AP. In contrast to the PR site, IR surface soils exhibited lower moisture and pH, but greater SOM levels. In addition, *Vicinamibacteriales* and *Gemmatimonadaceae* abundances increased in the IR surface soils, along with increased TP, TK, and AK. In addition, *Ardenticatenales* and *Fusarium* abundances decreased in IR surface soils, along with decreased TN, AP, AB, and UB. In the middle soil layers (20–40 cm), soil moisture was replenished by river and groundwater and there was no significant relationship between WFPR and soil moisture, while heat loss was an important characteristic of MS soils. Tp determined the ability of the middle soil layer water-holding capacity, while AFP determined the ability of the river to replenish soil water and soil water loss. Although MS soils did not lack the water needed for vegetation growth, vegetation requires greater temperatures, SOM, and available nutrients. When WFPR increased from 20% to 100%, middle soil Tp increased by 18.84%, AFP increased by 39.59%, SOM decreased by 85.38%, pH increased by 10.8%, and UB decreased by 46.12%, resulting in increased abundances of *Otidea* and *Fusarium* in middle soils along with the increase in TK and AK. Concomitantly, the abundances of *Gemmatimonadaceae* and *Toментella* decreased, and AN, AP, TN, and TP decreased. In contrast to PR soils, IR surface soils exhibited greater moisture, while *Gemmatimonadaceae* and *Toментella* abundances increased along with AN, AP, and AK increases in conjunction with decreased abundances of *Otidea* and *Fusarium*. In deep soils (40–60 cm layers), soil moisture was usually saturated and thus, soil moisture was completely irrelevant to WFPR. Tp was the primary factor that affected DS soil moisture, but gas movement in soils was inhibited owing to space limitations. When WFPR increased from 20% to 100%, deep soil pH increased by 8.16%, and SOM increased by 58.29%, resulting in increased abundances of *Geopora* and *Otidea*, along with the increase in AK. Concomitantly, *Ardenticatenales* and *Toментella* abundances decreased along with the decreases in TP and AN. In 0–60 cm soil layers, BD was consistently negatively correlated with soil moisture, but this relationship was only significant in MS soils. When soil moisture was saturated or unsaturated, increased SOM always promoted the transformation of small soil aggregates to medium-sized aggregates. These results provided a more comprehensive understanding of ecosystem restoration at RRI soil ecosystems. These new insights provided more accurate scientific guidance for the construction of urban revegetations as well as a theoretical basis for investigating the effects of revegetation types on the functioning of RRI soil ecosystems.

Limitations of the study

NR, PR, and IR are constructed in the same river section. Thus, the soil physical, chemical, and biological properties are consistent ten years ago at the RRIs, and the river characteristics are consistent across the experimental sites. But the properties of river and RRI soils are unknown ten years ago. Therefore, our study only finds that revegetation can change the RRI ecosystem, and understand the specific differences in the RRI ecosystem in different revegetations. Our study cannot quantify changes in RRI ecosystems over ten years, nor can it predict the evolution of RRI ecosystems. In future studies, more time-series data are needed to monitor the dynamics of RRI ecosystems.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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AUTHOR CONTRIBUTIONS

Zihao Man: Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. Changkun Xie: Methodology, Software, Validation. Ruiyuan Jiang: Methodology, Software, Writing – review & editing. Anze Liang: Writing – review & editing. Hao Wu: Writing – review & editing. Shengquan Che: Conceptualization, Resources, Validation, Funding acquisition.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Critical commercial assays		
MoBio PowerLyzer PowerSoil DNA isolation kit	Mo Bio	Cat.12855
Deposited data		
Soil microbial community diversity data	This paper	Sequence Read Archive (SRA) accession numbers: PRJNA882231
Oligonucleotides		
338F	Majorbio Bio-Pharm Technology Co. Ltd.	5'-ACTCCTACGGGAGGCAGCAG-3'
806R	Major bio Bio-Pharm Technology Co. Ltd.	5'-GGACTACHVGGGTWTCTAAT-3'
ITS1F	Majorbio Bio-Pharm Technology Co. Ltd.	5'-CTTGGTCATTTAGAGGAAGTAA-3'
ITS2R	Majorbio Bio-Pharm Technology Co. Ltd.	5'-GCTGCGTTCTTCATCGATGC-3'

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Shengquan Che, chsq@sjtu.edu.cn.

Materials availability

This study did not generate new unique materials.

Data and code availability

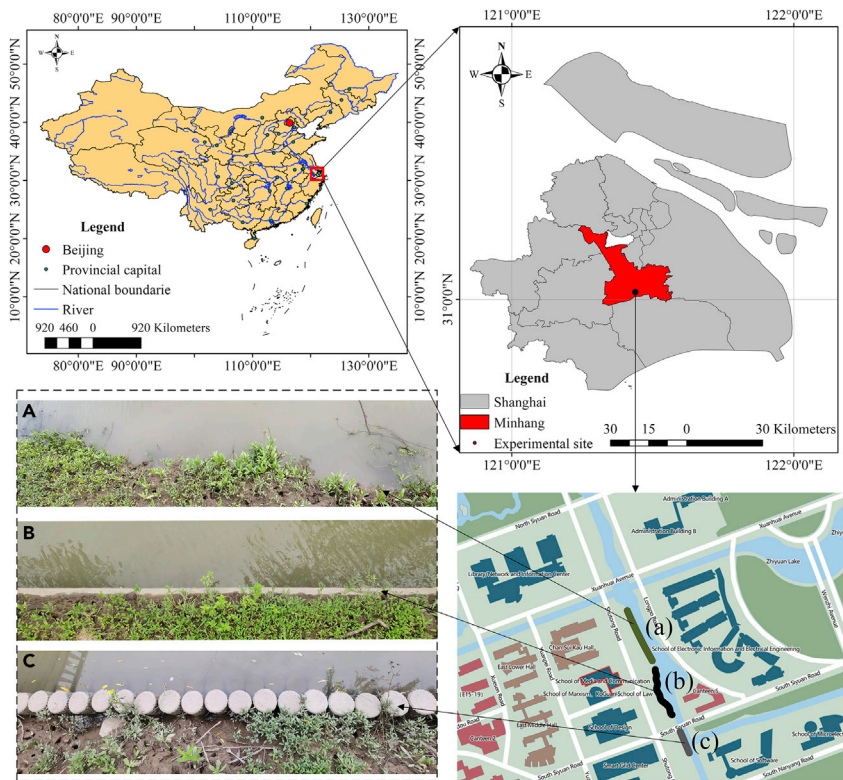
- Soil microbial community diversity data have been deposited at NCBI. Accession number are listed in the [key resources table](#).
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

METHOD DETAILS

Study area

Shanghai is located in eastern China where the Yangtze and Huangpu Rivers merge into the sea, encompassing an area of 6,340.5 km². The Shanghai area comprises an alluvial plain with an average elevation of 2.19 m. The region features a subtropical monsoon climate with an annual average temperature of 17.6°C, annual average precipitation of about 1,200 mm, and annual average sunshine of about 1,885 h.

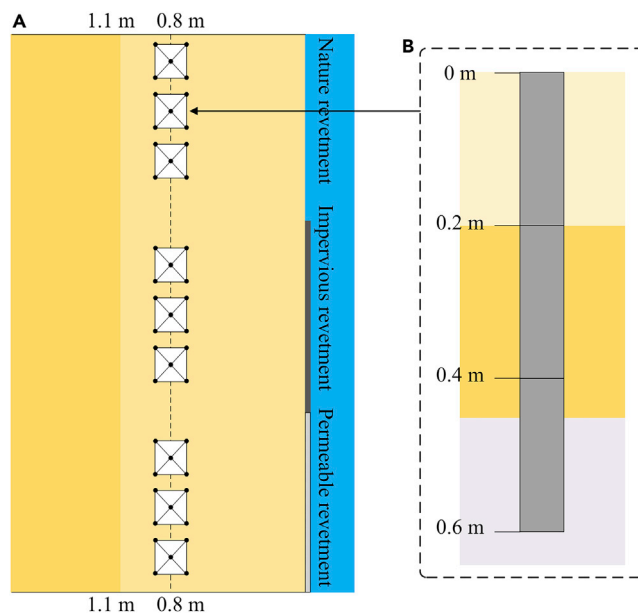
The experimental site for this study is located in the Minhang District of Shanghai (31°2'4" N, 121°26'16" E). NR (a), IR (b), and PR (c) are present in the same river section and arranged from north to south, exhibiting water-filled porosity of revetment (WFPR) values of 100%, 0%, and 20%, respectively (see below figure). WFPR represents the proportion of the volume that can be filled with water in the revetment, and is the volume available for water to flow divided by the total volume of the revetment. Importantly, river characteristics were consistent across the experimental sites (The river pH was 6.89 during the experiment, weakly acidic), mitigating problems that can arise from the difficulty in controlling field environmental factors across comparative sites. Revetments slowly change soil properties at RRI by affecting water migration, although this can take a long time. The revetments in this study were constructed 10 years ago in the same river section, and the construction was simultaneous, no soil replacement. Thus, the soil properties were consistent at the RRI when revetments were just completed. In addition, the primary herb species is the same across the RRI of the experimental site (*Kalimeris indica* (L.) Sch. – *Bip*). These herbs are minimally affected by human activities, and no aquatic plants are present in the river.



Experimental location and retentment types for the (A) natural retentments, (B) permeable retentments, and (C) impervious retentments sites

Field sampling

Sampling was conducted in August 2021, because herbs had already grown at this time. RRI width is about 1.1 m, which is measured through the scale (In the area that is frequently affected by the river, the vegetation growth is very special, and there is a very clear dividing line.). And samples were collected 0.8 m from



Sampling location information, (A) is the layout of the plot, (B) is the depth of soil sample collection in the plot

the revetment. Three samples were used for each revetment (see below figure) to ensure that the micro-habitat conditions are representative of each site. In addition, five points were used for each sample to ensure data accuracy across sampling points. The study area features a hot climate, high surface soil evaporation, and high groundwater levels. Generally, water is more present in soils below 50 cm. Consequently, soil samples at depths of 20 cm, 40 cm, and 60 cm were collected. The soils at 0–20 cm are referred to as surface soil (SS), 20–40 cm layers are middle soil (MS), and 40–60 cm layers are deep soil (DS). A portion of the soil samples was used to measure soil physical properties, ensuring that the soil structures were not destroyed. Another portion of the soil samples was used to measure soil chemical and microbial properties. The five samples from each sampling square were evenly pooled to represent a composite for that sample. The data shown here are averages for the three samples at the RRI.

Soil physical and chemical properties

Soil moisture and temperature were measured using a three-parameter soil meter (DELTA-T, UK). Undamaged soil samples were used, followed by drying in a ring knife and measuring soil bulk density (BD). The soil in the ring knife was placed in water and the volume of the soil was calculated after discharging air, followed by weighing soils after drying, in addition to calculating soil specific gravity (SG). Soil texture was measured using the specific gravity method (Han et al., 2016). Total porosity (T_p) was calculated based on BD and specific gravity (Equation 1). Capillary porosity (CP) was calculated as the ratio of capillary water volume to the total soil volume, while air-filled porosity (AFP) was calculated as the difference between T_p and CP. Soils were mixed with water at 5:1 ratios and soil pH was measured with a pH meter. Soil total nitrogen (TN), total phosphorus (TP), and total potassium (TK) were measured with an elemental analyzer (Vario Macro Cube, Elementar Analysensysteme GmbH, Germany). Soil available phosphorus (AP), available potassium (AK), available nitrogen (AN) were measured with a soil nutrient detector (LD-GT4, Lynd, China). SOM was calculated by measuring the amount of heated potassium dichromate needed to oxidize organic carbon.

$$T_p = \left(1 - \frac{BD}{SG}\right) \times 100 \quad (\text{Equation 1})$$

Soil bacterial community composition

To evaluate soil bacterial community compositions, microbial DNA was extracted from 5 g of soil using a MoBio PowerMax Soil DNA Isolation Kit (MoBio Laboratories, Carlsbad, CA, USA), followed by measurement of DNA concentrations with a NanoDrop ND-1000 UV-Vis spectrophotometer (NanoDrop Technologies, USA). The V3-V4 hypervariable regions of bacterial 16S rRNA genes were amplified using the bacteria-specific primers 338F (5'-ACTCCTACGGGAGGCAGCAG-3') and 806R (5'-GGACTACHVGGGT WTCTAAT-3') in PCR amplifications. PCRs were performed using a PTC 100 thermal cycler (MJ Research, Waltham, MA, USA), followed by the separation of products with gel electrophoresis. Fragments 500–600 bp in size were excised from gels and extracted using a Qiagen Gel Extraction Kit (Qiagen, Valencia, CA), followed by purification with a Qiagen PCR Purification Kit (Qiagen). Amplification products were combined in equal concentrations and amplicons were sequenced using the Illumina HiSeq platform (Illumina, San Diego, CA, USA) (Xu et al., 2016).

Soil fungal community compositions

To evaluate fungal community compositions, 400 mL of Miller Phosphate Buffer and Miller SDS lysis buffer were added to samples along with 450 mL of 25:24:1 phenol: chloroform: isoamyl alcohol. Sample tubes were then homogenized using a Biospec Mini 8 bead mill (Biospec, Bartlesville, OK, USA) at full speed for 1 min. Then, 560 mL of the supernatant was centrifuged and DNA was extracted from the precipitate using a MoBio Power Soil DNA Extraction Kit (Carlsbad, CA, USA). The ITS1 regions of fungal ITS genes were then amplified using the fungal-specific PCR primers ITS1F (5'-CTTGGTCATTTAGAGGAAGTAA-3') and ITS2R (5'-GCTGCGTTCCTCATCGATGC-3'). Samples were PCR-amplified in triplicate and pooled before cleaning with AMPure magnetic beads (Beckman Coulter Genomics, Danvers, MA, USA). A Qubit fluorometer (Invitrogen, Carlsbad, CA, USA) was used to quantify individual amplicon samples and they were combined at equimolar concentrations. Finally, 1/8th of a 454 FLX Titanium pico-titer plate was used for ITS sequencing (Adams et al., 2013).

Herb biomass measurements

A 20 × 20 cm sample was selected for measuring herb biomass. The above-ground portion of the herb was excised, followed by cleaning and storage in a sealed bag. Using the 20 × 20 cm square as the boundary, a 40 cm depth soil block was excavated and the underground roots were cleaned and stored in sealed bags. The weights of the aboveground and underground portions of the herbaceous plants were measured by drying at 90°C to a constant weight, followed by calculation of aboveground (AB) and underground biomass (UB) (Man et al., 2019).