Soil fauna diversity at different stages of reed restoration at a lakeshore wetland at Lake Taihu, China

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ABSTRACT

Introduction: Wetland soil fauna support material cycling and restoration processes in wetland ecosystems. In our study, we observed variations in wetland soil fauna on the shores of Lake Taihu, China. We examined the relationships between fauna and major environmental factors, and looked at the short-and long-term changes in reed wetlands under restoration and in the natural reed lakeshore.

Outcomes: We identified 93 groups of soil fauna in different wetlands and found significant differences in the lakeshore wetlands’ soil fauna assemblages, depending on the length of the restoration period. By analyzing the soil fauna community evenness, dominance, number of taxa, and diversity, we found minimal seasonal variation in the soil fauna community diversity and abundance. The abundance of soil fauna in the sites under restoration decreased with depth below the soil surface. The reed restoration was obvious in the succession of the soil fauna groups in the long-term site. Although the restoration had an overall positive long-term effect on the soil fauna communities, there were no obvious short-term changes in the number of individuals.

Conclusion: The study explored various potential measures to restore soil fauna in the Lake Taihu wetland and developed a theoretical basis for restoring the lakeshore wetland ecosystem.

Introduction

Wetlands play an indispensable role in preventing floods, balancing hydrological and climatic cycles, protecting biological diversity, controlling pollution, minimizing the impacts of drought, and conserving water resources. As one of the most biologically productive ecosystems on the planet, they are a haven for rare waterfowl and have been referred to as the cradle of life and the kidney of the Earth (Cui and Asselin 2006; Broeck et al. 2015). However, as elsewhere, China’s wetlands have been experiencing unprecedented degradation and have been decreasing in extent since the beginning of the twentieth century. Because of a general lack of understanding about the overall value of wetland ecosystems, these areas are threatened by the ongoing industrialization and urbanization that have resulted from the country’s booming economy and very dense urban populations (Yin 2003).

Lakeshore restoration, a type of wetland restoration, is used to maintain the stability and ecological characteristics of lakeshore zones (National Research Council 2002; Haskell et al. 2018). When implemented appropriately, restoration projects can effectively slow down the wetland degradation process and improve the structure and functions of degraded wetland ecosystems.

Wetland restoration should be monitored and managed to ensure that recovery project measures are adequately and appropriately implemented. Monitoring is very important when restoring and managing wetland, and objectively evaluating wetland restoration (Cui et al. 2011; Pan et al. 2013; Hazeltine et al. 2019).

Recently, changes in soil fauna communities and diversity have been the focus of many studies as both of these are useful for studying degraded ecosystems. Researchers have previously used the number and population densities of soil fauna as indicators of soil health (Longcore 2003; Caruso, Taormina, and Migliorini 2012; Khemaisia et al. 2018; Ma, Yin, and Wang 2019). The effects of wetland restoration on soil fauna are mainly reflected in the succession of soil fauna groups and the respective abundances of those groups (Liu et al. 2014; Cui et al. 2016). When a wetland is degraded, the complexity of the soil fauna species composition and the numbers of individual fauna decrease, which then impacts on the ability of wetland soils to carry out ecosystem services. However, in the early stages of wetland recovery, there are few obvious changes in the composition of wetland soil fauna communities (Mitsch and Wang 2000; Cui et al. 2011; Antón-Pardo and Armengol 2016). Further, the functions of many of the different soil fauna within wetland ecosystems (e.g.,...
decomposition of soil organic matter, nutrient cycling, improvements to the soil structure, and effects on soil health and plant succession) are interconnected (Burger et al. 2003; Ma, Yin, and Wang 2019), and so soil fauna can serve as ecological indicators in areas of wetland that are under restoration. Soil fauna are important for understanding ecosystem status, and the effects of, and patterns associated with, wetland restoration. Monitoring of soil fauna can support the development of tools for wetland monitoring, evaluation, and management (Volkmar 2001; Anke and Rosenzweig 2003; Andrésa and Mateos 2006; Yin et al. 2008; Jiao et al. 2019). In recent years, studies of soil fauna have gradually shifted to functional research, while studies of degraded wetland restoration have started to examine how the wetland soil fauna change over the restoration period in greater detail (Hunt and Wall 2002; Zedler 2011). Indeed, soil fauna are used in studies of wetland restoration as biological indicators of successful restoration (Hartmut 1998; Neher 2001; Bissett et al. 2016).

In this study, we conducted a large-scale field investigation between April 2010 and February 2011 and then analyzed the soil fauna to gain improved insights into the species composition, abundance, and distribution of soil fauna in wetland ecosystems around Lake Taihu. We chose three study sites in reed-dominated wetlands along the banks of Lake Taihu, including a long-term reed restoration lakeshore, a short-term reed restoration lakeshore, and a natural reed lakeshore. The three sites had similar soil conditions and histories. The objectives of this study were to evaluate the composition of, and differences between, the soil fauna communities in wetlands at different stages of restoration; to determine the abundance and diversity of soil fauna at different stages of reed wetland restoration, and to gain insights into how the soil fauna changed at different stages in the restoration process.

**Materials and methods**

**Study area**

Lake Taihu is located in the south of the Yangtze River Delta, China. It is the third-largest freshwater lake in China, and has an area of more than 2400 km². The mean annual temperature in this area is approximately 17°C and the mean annual rainfall is approximately 1096.7 mm (Jin, Liu, and Yi 1995; Hu et al. 2011). The study area was mainly along the east coast of Lake Taihu, where the average altitude was approximately 4 m. The vegetation species in the wetland areas under restoration and the natural sites were dominated by *Phragmites australis* and *Alternanthera philoxeroides*. Reeds were the target vegetation of the wetland restoration, so the recovery of the lakeshore was assessed by the extent of the natural restoration of the reeds. In this study, the lakeshore area that had been recovering for more than five years was referred to as long-term reed restoration lakeshore site (LR) (site A), while the area that had been recovering for only two years was referred as short-term reed restoration lakeshore site (SR) (site B). An area of natural wetland with reeds on the lakeshore (NR) was also chosen (site C). The sampling sites are shown in Figure 1.

**Soil fauna sampling**

We selected the sampling sites after examining high-definition remote sensing images and topographic maps (Hestir et al. 2015), and carrying out initial field surveys. Samples were collected from plant communities that represented the different habitats at three sites, along lengths of 3 km, in the lakeshore wetland area on the eastern side of Lake Taihu. We randomly selected 5 samples at each site on 4 sampling occasions, namely April, August, and November of 2010, and in February 2011. The soil samples were divided into 3 layers, from 0–5 cm, 5–10 cm, and 10–15 cm.

![Figure 1. Study sites of Lake Taihu.](image-url)
(Orozco, Lee, and Stock 2014). The volume and diameter of the cylindrical soil samples were 115 ml and 5.4 cm, respectively. We also took samples with a volume of 20 × 20 × 5 cm, corresponding to the 3 soil layers. Thus, we collected 5 large samples, each of which was divided into 3 layers, in 3 different sites, on 4 sampling events, making a total of 180 samples.

**Soil fauna identification**

The large samples were collected manually, preserved in a 75% alcohol solution, and then transported to the laboratory for initial identification (Handbook of Soil Animal Research Methods 1998; Yin 2000). We identified and counted the isolated soil fauna under an Olympus SZX16 stereo microscope (Olympus, Tokyo, Japan). We used Tullgren and Baermann funnels to separate the soil fauna by size (Lakly and Crossley 2000; Rodgers et al. 2018) over periods of 24 h and 48 h, respectively. Most of the small arthropods can be collected with the Tullgren funnel (primarily medium-sized soil fauna), and the aquatic or wet soil fauna can be separated with the Baermann funnel. The soil fauna were separated following the procedures outlined in the Soil Animal Retrieval Guide of China (Yin 1998) under a Leica DM4000B light microscope (Leica, Wetzlar, Germany) and Olympus SZX16 stereo microscope (Olympus, Tokyo, Japan) and then were classified and counted.

**Soil sampling**

Soil samples that corresponded to the soil fauna sampling sites were collected using the ring knife method, placed in a collection bag, and taken to the laboratory for analysis, in line with conventional methods (Yin 2000). Samples were analyzed for seven indicators, namely soil pH, soil organic matter (SOM), total phosphorus (TP), total nitrogen (TN), moisture content (MC), soil temperature, and electrical conductivity (Cond) (Warren and Zou 2002; Murray et al. 2006; Liu, Zhao, and Zhao 2012). We measured the MC and temperature in the field using a Procheck soil moisture sensor (Decagon, USA).

**Statistical analyses**

We used the Simpson Diversity, Shannon–Wiener Diversity, and Pielou Evenness (Ma 1994) indices to evaluate the different vegetation cover types and characteristics of the changes in the species composition of the soil fauna communities. The Simpson Diversity Index, Shannon–Wiener Diversity Index, and Pielou Evenness Diversity Index were calculated with Equations (1)–(3), respectively.

\[
D = 1 - \sum_{i=1}^{S} N_i(N_i - 1)/N(N - 1) \tag{1}
\]

\[
H = - \sum_{i=1}^{S} P_i \ln P_i \tag{2}
\]

\[
E = H/\ln S \tag{3}
\]

where \( N \) represents the total number of all types of individual species, \( N_i \) represents the number of individuals of a species \( i \), \( P_i \) represents the \( i \)th species in the proportion of the total number of species, and \( S \) represents the number of species. To determine the abundance, we used the Morisita–Horn Index (Equation (4)):

\[
Cmh = \frac{2(aN)(bN) \sum_{i=1}^{S} [ (an_i)(bn_i) ]}{bN^2 \sum_{i=1}^{S} an_i^2 + aN^2 \sum_{i=1}^{S} bn_i^2} \tag{4}
\]

where \( S \) is the number of all the groups; \( aN \) is the total number of individuals of all groups for type A, \( bN \) is the total number of individuals of all groups for type B; \( an_i \) is the number of groups in the \( i \)th number of individuals for type A, and \( bn_i \) is the number of groups in the \( i \)th number of individuals for type B.

The average density of soil fauna was determined by the number of individual soil fauna per square meter (number/m²). Before analysis, the soil fauna data were logarithmically transformed. For normally distributed soil fauna data we analyzed the individual numbers of different types of soil fauna by single-factor analysis of variance (one-way ANOVA). We used Duncan’s multiple range test to determine whether any differences were significant. We used the Kruskal–Wallis (\( H \)) nonparametric test to analyze soil fauna data that were not normally distributed.

Canonical correspondence analysis (CCA) was used to sort the data and analyze the relationships between the soil fauna and the soil physical and chemical properties (Guisan, Weiss, and Weiss 1999; Zhang 2004; Liu, Gao, and Wu 2017). The soil fauna from the three study sites and ten soil environmental properties monitored in four sampling events were sequenced using the CCA. The correlations between the distributions of ten soil characteristics (soil pH, SOM, TN, TP, AP, ammonium (NH₄-N), potassium (K’), soil MC, soil temperature and Cond) and the corresponding distributions of the soil fauna communities were also determined with CCA (Bruehlheide et al. 2002; Zhang and Chu 2013). Groups that have less than 1% of the total number of individuals were excluded from the analysis. The soil fauna community data were transformed logarithmically to decrease the weight of the dominant soil fauna communities.
**Results**

**Different densities of soil fauna community species composition during reed recovery**

During the sampling events (April, August, and November 2010, and February 2011), 93 groups of soil fauna were identified. At the long-term reed restoration lakeshore, short-term reed restoration lakeshore, and natural reed lakeshore 71, 51, and 63 soil fauna groups were identified, respectively (Table 1). The dominant groups at the long-term reed restoration lakeshore were Enchytraeidae, Diplopoda, and Nematoda were dominant groups, accounting for 22.44%, 21.01%, and 19.35% of the total number of individuals, respectively. Nematoda, accounting for 23.02%, dominated at the short-term reed restoration lakeshore, followed by Acari with 7.22% of the total number of individuals. Nematoda dominated, and accounted for 33.83% of the total number of individuals, at the natural reed lakeshore.

The percentage of each group corresponds to the proportion of individuals in the group out of the total number of individuals in all groups.

**Soil fauna density over time at different stages of reed restoration**

The soil fauna density was higher (but not significantly) in April 2010 than in the three other months ($P > 0.05$) (Figure 2), which indicates that the soil fauna in the reed wetland areas were not particularly sensitive to seasonal changes. There were no significant differences between the long-term reed restoration lakeshore, short-term reed restoration lakeshore, and natural reed lakeshore in the same month ($P > 0.05$). Overall, the soil fauna density was lowest at the short-term reed restoration lakeshore and highest at the long-term reed restoration lakeshore.

**Community diversity of soil fauna in reed restoration wetlands**

Analysis of the soil fauna diversity reflects both the complexity of the soil fauna species distribution and the stability of habitats, and the similarities and differences between different habitats (Bradford et al. 2002; Goncalyes and Pereira 2012). The results from dominance variance analysis showed that there was no significant difference ($P > 0.05$) (Figure 3) in the diversity of the samples in November 2010 and February 2011. Furthermore, the results from analysis of variance among the different community types showed that there was no significant difference between the three habitat types during the four survey periods ($P > 0.05$). Evenness is a measure of the relative abundance of different species in a community (Rudolf et al. 2016). The uniformity is at a maximum when all the species in a community have an equal number of individuals (Brady et al. 2002) and is at a minimum when all the individuals belong to a single species.

Analysis of the uniformity within the same month showed that the soil fauna composition differed significantly ($H = 15.052, P < 0.05$) in soil fauna composition between the long-term reed restoration lakeshore and the natural reed lakeshore in August 2010. However, there were no other significant differences between habitat types during other periods ($P > 0.05$); and analysis of variance of soil fauna diversity showed that there was no significant difference ($P > 0.05$) between the various wetland areas. There were no significant differences in the other factors studied, including the dominance, group number, and diversity indices. There were also no significant differences over the four study periods, indicating that the soil fauna diversity varied little by season, though the diversity varied between the different areas. In addition, the diversity of the soil fauna communities at the three study sites was not significantly different.

**Vertical distribution of soil fauna at different stages of wetland restoration**

The vertical distribution of the soil fauna in the soil profile is shown in Figure 4. There were some differences in the individual density and group number along the soil profile between the four sampling periods. For example, the individual density in the surface soil at the natural site (0–5 cm) was significantly different from that at depths of 5–10 and 10–15 cm ($F = 17.120, P < 0.001$) in April, but the difference between 5–10 and 10–15 cm was not significantly different ($P > 0.05$). In August 2010, the individual density of the soil fauna in the surface soil layer was significantly different from that in the deeper (second or third) layers ($F = 6.269, P < 0.05$) at the short-term site, but the soil fauna individual densities at the three depths at the long-term reed restoration lakeshore and the natural reed lakeshore were not significantly different ($P > 0.05$). In November 2010, the individual density of soil fauna was significantly higher in the surface soil (first layer) than in the third or deepest layer at the long-term restoration lakeshore ($F = 3.079, P < 0.05$); similarly, soil fauna density was significantly higher in the surface soil (first layer) than in the second layer at the short-term reed restoration lakeshore ($F = 3.347, P < 0.05$). However, there were no significant differences between the three layers at the natural reed lakeshore ($P > 0.05$). In February 2011, there were no differences between the three soil layers at the different lakeshore ($P > 0.05$).

At the long-term reed restoration lakeshore, the number of soil fauna groups was significantly higher in the surface layer than in the second and third layers.
Table 1. Species richness and abundance of soil fauna at different stages of wetland restoration.

| Group (Latin name) | Individual (abundance) | Percent | Individual (abundance) | Percent | Individual (abundance) | Percent |
|--------------------|------------------------|---------|------------------------|---------|------------------------|---------|
| Mollusca           |                        |         |                        |         |                        |         |
| Gastropoda         | 20                     | 1.51    | 9                      | 1.23    | 6                      | 0.64    |
| Bivalvia           | 1                      | 0.08    |                        |         |                        |         |
| Nematoda           | 257                    | 19.35   | 169                    | 23.02   | 316                    | 33.83   |
| Oligochaeta        |                        |         |                        |         |                        |         |
| Lumbricida         | 67                     | 5.05    | 22                     | 3.00    | 19                     | 2.03    |
| Enchytraeida       | 298                    | 22.44   | 32                     | 4.36    | 60                     | 6.42    |
| Hirudinea          |                        |         |                        |         |                        |         |
| Arthropoda         |                        |         |                        |         |                        |         |
| Malacostraca       |                        |         |                        |         |                        |         |
| Amphipoda          | 26                     | 1.96    |                        |         | 1                      | 0.11    |
| Isopoda            | 4                      | 0.30    | 42                     | 5.72    | 9                      | 0.96    |
| Porcellionida      | 13                     | 0.98    | 1                      | 0.14    | 1                      | 0.11    |
| Oniscidae          | 6                      | 0.45    |                        |         |                        |         |
| Armadillida        |                        |         |                        |         |                        |         |
| Chilopoda          |                        |         |                        |         |                        |         |
| Scolopendromorpha  | 10                     | 0.75    | 6                      | 0.82    |                        |         |
| Geophilomorpha     | 8                      | 0.60    | 21                     | 2.86    | 16                     | 1.71    |
| Lithobiomorpha     | 1                      |         | 1                      | 0.14    | 1                      | 0.11    |
| Diplodopa          | 279                    | 21.01   | 45                     | 6.13    | 5                      | 0.54    |
| Symphyla           | 24                     | 1.81    | 16                     | 2.18    | 4                      | 0.43    |
| Pauropoda          | 1                      | 0.08    | 5                      | 0.68    | 2                      | 0.21    |
| Collombola         |                        |         |                        |         |                        |         |
| Onychiuridae       | 13                     | 0.98    | 29                     | 3.95    | 53                     | 5.67    |
| Hypogastruridae    | 11                     | 0.83    | 39                     | 5.31    | 25                     | 2.68    |
| Isotomidae         | 12                     | 0.90    | 46                     | 6.27    | 45                     | 4.82    |
| Entomobryidae      | 9                      | 0.68    | 22                     | 3.00    | 25                     | 2.68    |
| Sminthuridae       | 2                      | 0.15    | 1                      | 0.14    |                        |         |
| Neanuridae         | 38                     | 2.86    | 6                      | 0.82    | 9                      | 0.96    |
| Diplura            |                        |         |                        |         |                        |         |
| Japygida           | 5                      | 0.38    | 3                      | 0.41    | 1                      | 0.11    |
| Insecta            |                        |         |                        |         |                        |         |
| Archaeognatha      | 2                      | 0.15    |                        |         |                        |         |
| Orthoptera         |                        |         |                        |         |                        |         |
| Gryllotalpidae     | 1                      | 0.08    | 1                      | 0.14    | 1                      | 0.11    |
| Myrmecophilidae    | 1                      |         | 1                      | 0.14    |                        |         |
| Tridactylidae      | 12                     | 0.90    | 1                      | 0.14    | 3                      | 0.32    |
| Acridida           | 2                      | 0.15    |                        |         |                        |         |
| Isoptera           |                        |         |                        |         |                        |         |
| Termitidae         | 5                      | 0.38    |                        |         |                        |         |
| Corrodentia        |                        |         |                        |         |                        |         |
| Liposcelididae     | 7                      | 0.53    | 2                      | 0.27    | 43                     | 4.60    |
| Sphaeroscopidae    |                        |         |                        |         | 1                      | 0.11    |
| Dermoptera         |                        |         |                        |         |                        |         |
| Forficulidae       | 5                      | 0.38    | 17                     | 2.32    | 12                     | 1.28    |
| Spongiphoridae     | 2                      | 0.15    | 2                      | 0.21    |                        |         |
| Thysanoptera       |                        |         |                        |         |                        |         |
| Phlaeothripidae    | 5                      | 0.38    |                        |         |                        |         |
| Homoptera          |                        |         |                        |         |                        |         |
| Aphididae          | 2                      | 0.27    | 1                      | 0.11    |                        |         |
| Hemiptera          |                        |         |                        |         |                        |         |
| Cydnidae           | 2                      | 0.15    |                        |         |                        |         |
| Enicocephalidae    |                        |         |                        |         |                        |         |
| Lygaeidae          | 5                      | 0.38    | 1                      | 0.14    | 12                     | 1.28    |
| Ochteridae         | 2                      | 0.15    |                        |         |                        |         |
| Reduviidae         | 1                      | 0.08    | 1                      | 0.14    |                        |         |
| Scutelleridae      | 1                      | 0.15    |                        |         |                        |         |
| Hebridae           | 2                      | 0.15    |                        |         |                        |         |
| Coleoptera         |                        |         |                        |         |                        |         |
| Staphylinae        | 21                     | 1.58    | 32                     | 4.36    | 20                     | 2.14    |
| Histeridae         | 1                      | 0.08    |                        |         |                        |         |
| Hydrellidae        | 1                      | 0.08    |                        |         |                        |         |
| Phalaenidae        | 1                      | 0.08    |                        |         |                        |         |
| Ptiliidae          | 1                      | 0.08    |                        |         |                        |         |
| Diphyllidae        |                        |         |                        |         | 1                      | 0.11    |
| Pselaphidae        | 1                      | 0.08    | 10                     | 1.36    | 1                      | 0.11    |
| Carabidae          | 3                      | 0.23    | 10                     | 1.36    | 28                     | 3.00    |
| Letidae            | 3                      | 0.23    | 1                      | 0.11    |                        |         |
| Erotylidae Latreille | 2                     | 0.15    |                        |         |                        |         |
| Chrysomelidae      | 1                      | 0.08    |                        |         |                        |         |
| Scarabaeidae       | 1                      | 0.08    |                        |         |                        |         |
| Tenebrionidae      | 0                      | 2       | 2                      | 0.21    |                        |         |
| Scolytidae         | 5                      | 0.38    | 4                      | 0.43    |                        |         |
| Carabidae larva    | 5                      | 0.38    | 3                      | 0.41    | 17                     | 1.82    |

(Continued)
In April 2010, the number of groups was significantly higher in the surface layer than in the third layer ($F = 3.181, P = 0.05$) in April 2010. Also, at this lakeshore the number of groups was significantly higher in the surface layer than in the third layer ($F = 5.926, P < 0.01$) in August, while the number of groups in the surface layer was significantly higher than in the second and third layers ($F = 8.312, P < 0.01$) in November. There

| Group (Latin name) | Individual (abundance) | Percent | Individual (abundance) | Percent | Individual (abundance) | Percent |
|--------------------|------------------------|---------|------------------------|---------|------------------------|---------|
| Staphylinidae larva | 1                      | 0.08    | 7                      | 0.95    | 6                      | 0.64    |
| Ptiliidae larva    | 1                      | 0.08    |                        |         |                        |         |
| Lampryridae larva  | 1                      | 0.08    |                        |         |                        |         |
| Scarabaeidae larva |                        |         |                        |         |                        |         |
| Scydmaenidae larva |                        |         |                        |         |                        |         |
| Cucullonidiae larva| 1                      | 0.08    | 2                      | 0.27    | 1                      | 0.11    |
| Diptera            |                        |         |                        |         |                        |         |
| Mycetophilidae     | 2                      | 0.15    | 3                      | 0.41    | 7                      | 0.75    |
| Muscidae           | 2                      | 0.15    |                        |         | 28                     | 3.00    |
| Psychodidae        | 7                      | 0.53    | 2                      | 0.27    | 1                      | 0.11    |
| Scaridae           |                        |         |                        |         | 2                      | 0.21    |
| Syrphidae          |                        |         |                        |         | 1                      | 0.11    |
| Simuliidae         |                        |         |                        |         |                        |         |
| Agrromyidae        | 3                      | 0.23    | 1                      | 0.14    | 3                      | 0.32    |
| Bibionidae         | 1                      | 0.14    |                        |         |                        |         |
| Drosophilidae      | 1                      | 0.11    |                        |         |                        |         |
| Tipulidae          | 1                      | 0.08    |                        |         |                        |         |
| Dolichopodidae     | 2                      | 0.15    | 1                      | 0.14    | 1                      | 0.11    |
| Dolichopodidae larva |                |         |                        |         |                        |         |
| Chironomidae larva | 1                      | 0.08    | 1                      | 0.14    | 3                      | 0.32    |
| Ceratopogonidae larva |            |         |                        |         | 3                      | 0.54    |
| Muscidae larva     | 4                      | 0.30    | 3                      | 0.41    | 2                      | 0.21    |
| Hymenoptera        |                        |         |                        |         |                        |         |
| Chalcididae        |                        |         |                        |         |                        |         |
| Formicidae         | 17                     | 1.28    | 29                     | 3.95    | 30                     | 3.21    |
| Formicidae larva   | 4                      | 0.43    |                        |         |                        |         |
| Lepidoptera        |                        |         |                        |         |                        |         |
| Pieridae larva     | 3                      | 0.23    | 1                      | 0.14    | 1                      | 0.11    |
| Arachnida          |                        |         |                        |         |                        |         |
| Salticidae         |                        |         |                        |         |                        |         |
| Lycosidae          |                        |         |                        |         |                        |         |
| Zoridae            | 2                      | 0.15    | 1                      | 0.14    | 3                      | 0.32    |
| Liocranidae        | 7                      | 0.95    |                        |         | 9                      | 0.96    |
| Zodariidae         |                        |         | 2                      | 0.21    |                        |         |
| Gnaphosidae        | 5                      | 0.38    | 5                      | 0.68    | 10                     | 1.07    |
| Acanthorhinae      | 13                     | 0.98    | 11                     | 1.50    | 12                     | 1.28    |
| Pseudoscorpionida  |                        |         | 1                      | 0.08    |                        |         |
| Acanthorhinae      | 54                     | 4.07    | 53                     | 7.22    | 46                     | 4.93    |
| Total numbers      | 1328                   | 100.00  | 734                    | 100.00  | 934                    | 100.00  |
| Total groups       | 71                     |         | 51                     |         | 63                     |         |

Long-term reed restoration lakeshore (LR), short-term reed restoration lakeshore (SR), natural reed lakeshore (NR). The percentage of each group corresponds to the proportion of individuals in the group out of the total number of individuals in all groups.

Figure 2. Densities of soil fauna in the three different wetland areas. The bars represent the mean values and the error bars represent the standard error.
were no significant differences in the number of groups among soil layers at the long-term reed restoration lakeshore in February 2010.

At the short-term reed restoration lakeshore, the number of groups in the surface layer was significantly different from the numbers in second and third layers \( (F = 6.962, \ P < 0.01) \) in August 2010, but there were no significant differences between the layers in the other months. At the natural reed lakeshore, the number of groups in the surface layer was significantly different from the numbers in the second or third layers \( (F = 4.303, \ P < 0.05) \) in April 2010, while in August 2010 the number of groups was significantly higher in the surface layer than in the third layer \( (F = 3.794, \ P < 0.05) \). Still, at the natural lakeshore the numbers of groups in the surface and third layers were significantly different \( (F = 3.316, \ P < 0.05) \) in November 2010, the numbers of groups in the different soil layers were not significantly different in February 2011.

**Relationships between the fauna at the different reed restoration lakeshore and soil environmental factors**

Analysis of the soil and environmental factor axes for April 2010 showed that the first axis reflected mainly \( K^+ \) and Cond; and the second ordination axis reflected the temperature \( (Table 2) \), while, in August 2010, the first ordination axis reflected the soil MC and Cond, and the second ordination axis reflected TP and Cond. The first ordination axis reflected soil MC and the second axis reflected AP in November 2010, while the first ordination axis reflected TP, \( K^+ \), and Cond, and the second axis reflected the AP in February 2010.

**Figure 5** reflects the overall nature of the relationship between the soil properties at the different sites and the composition of the soil fauna communities for the four sampling events. In April 2010, there was a long arrow connecting the first ordination axis and soil \( K^+ \) and Cond, indicating a significant correlation between the first ordination axis and soil properties \( K^+ \) and Cond. The arrow between the second ordination axis and temperature was also long, again indicating a significant correlation between the second axis and temperature. The relationship between the environment variables and the ordination axes is shown in **Table 3**. As shown in **Figure 5**, Bourletiella (Collembola), Symphyla and Armadillidae (Isopod) were mainly influenced by \( K^+ \), while Staphylinidae (Coleoptera) larvae were mainly affected by temperature. Soil environmental factors had a minimal influence on Muscidae (Diptera), Chironomid, Psychodidae, and Scydmaenidae (Coleoptera) larvae.

In August 2010, there was a long arrow connecting the first ordination axis and soil MC and Cond, indicating a significant correlation between the first ordination axis and MC and Cond. The arrow between the second ordination axis and TP and Cond was also long, indicating a significant correlation between the second ordination axis and TP and Cond. Here, we see that MC had a considerable effect on
Muscidae larvae (Diptera), while soil conductivity had a considerable effect on Phlaeothripidae (Thysanoptera). Lygaeidae (Hemiptera) was strongly influenced TP, while soil environmental factors had a minimal effect on Chilopoda Geophilomorpha and Hemiptera Lygaeidae.

In November 2010, there was a long arrow between the first ordination axis and soil MC, indicating a significant correlation between the first ordination axis and soil MC. The arrow between the second ordination axis and AP was also long, indicating a significant correlation between the second ordination axis and AP. Here, we see that AP had a considerable effect on Psocoptera, and MC had a considerable effect on Symphyla. Soil environmental factors had little effect on Araneae, Gnaphosidae, and Coleoptera Pselaphidae.

Figure 4. Diversity of the soil fauna communities at different stages of restoration. The bars in figures represent the mean values and the error bars represent the standard error.
In February 2011, there was a long arrow between the first ordination axis and soil TP, K+, and Cond, indicating a significant correlation between the first axis and soil TP, K+, and Cond. The arrow between the second ordination axis and AP was also long, indicating a significant correlation between the second axis and AP. Here, we see that TP had a strong effect on Chilopoda Geophilomorpha, while soil environmental factors had little effect on Isopoda, Collembola Neanuridae, and Coleoptera Staphylinidae.

Abbreviations: Eritrylidae: Eroty; Acari: Ac; Agromyjidae: Agrom; Amphipoda: Amph; Aphididae: Aphid; Armadillidae: Armad; Carabidae: Carab; Carabidae larva: Carab Lar; Ceratopsogonida larva: Cerat Lar; Chironomidae: Chiro; Chironomidae larva: Chiro Lar; Corrodentia: Corro; Curculionidae larva: Curcu Lar; Diplopoda: Diplo; Dolichopodidae larva: Dolic Lar; Enchytraeidae: Enchy; Entomobryidae: Entom; Forficulidae: Forf; Formicidae: Form; Gastropoda: Gas; Geophilomorpha: Geophil; Gnatopodidae: Gnaph; Hypogastruridae: Hypog; Isoplano: Iso; Isotomidae: Isoto; Japygidae: Japyg; Leiodoridae: Leiod; Liocaridacea: Lioc; Liposcelididae: Lipos; Lithobiomorpha: Litho; Lumbriida: Lumbr; Lycosidae: Lycos; Lygaeidae: Lygae; Muscidae larva: Musc; Myctophilidae: Myct; Neanuridae: Nean; Nematoda: Nemat; Ochteridae: Ochte; Onychiuridae: Onych; Phlaeothripidae: Phla; Pieridae larva: Pier Lar; Porcellionidae: Porc; Pselaphidae: Psel; Psychodidae: Psych; Scopelendromorpha: Scolo; Scydmaenidae: Scyd; Scydmaenidae larva: Scyd Lam; Sminturidae: Smint; Spongiphoridae: Spong; Staphylinidae: Staph; Staphylinidae larva: Staph Lar; Symphyta: Symph; Tritylidae: Trida; Zodaroidae: Zodar

**Discussion**

The results show that there was a high heterogeneity of species in the soil fauna communities in the wetland areas that were subject to reed restoration over different time periods. While there were few individuals in the rare and extremely rare taxa groups, some of them were physically large, and included earthworms, Diptera larvae, Coleoptera larvae, Cephalopods, and Chilopods (Table 1). These soil fauna are the main shredders of plant debris (Han et al. 2007; Fujii et al.)
and play an important role in material cycling (Ge et al. 2005; Ramírez-Fernández et al. 2019).

The results of our analyses of soil fauna community evenness, dominance, number of groups, and diversity indices showed that there were no significant seasonal differences in the soil fauna communities. Also, the soil fauna density was not sensitive to seasonal variations. While the uniformity (evenness) in the long-term reed

Figure 5. Canonical correspondence analysis ordination diagrams of soil fauna groups and environmental variables. The figures on the left represent the samples (circles); the figures on the right represent the soil fauna groups (triangles).
# Table 3. Canonical correlation analysis results.

|                | April 2010 | August 2010 | November 2010 | February 2011 |
|----------------|------------|-------------|---------------|---------------|
| Axes           | 1 2 3 4    | 1 2 3 4     | 1 2 3 4       | 1 2 3 4       |
| Eigen-values   | 0.372 0.195 0.137 0.111 | 0.379 0.357 0.267 0.17 | 0.334 0.21 0.184 0.148 | 0.442 0.325 0.302 0.204 |
| Species-environment correlations | 0.945 0.975 0.893 0.838 | 0.979 0.978 0.942 0.918 | 0.996 0.976 0.981 0.992 | 0.981 0.969 0.991 0.978 |
| Cumulative percentage variance species data | 24.50 37.40 46.50 53.80 | 16.20 31.40 42.80 50.00 | 20.10 32.70 43.80 52.70 | 21.20 36.70 51.20 61.00 |
| species-environment relation | 35.00 53.30 66.20 76.60 | 22.90 44.50 60.70 71.00 | 27.40 44.70 59.90 72.00 | 26.30 45.50 63.50 75.60 |
| Sum of all Eigen-values | 1.515 | 2.344 | 1.662 | 2.088 |
| Sum of all canonical Eigen-values | 1.064 | 1.652 | 1.216 | 1.684 |
restoration lakeshore and natural reed lakeshore differed significantly in August 2010, the soil fauna community diversity in the three habitats was not significantly different over the other sampling periods, which indicates that the soil fauna community diversity varied little by season (Figure 3). However, the similarity did not differ significantly between the sampling events, indicating that there was little seasonal variation in the relative number of soil fauna communities, as reported by other authors (Wu et al. 2008; Wu and Wang 2019).

Generally, the number and types of soil fauna tend to decrease as the soil depth increased but the patterns in the numbers of individual fauna and groups and their relative abundances tend to differ between months (Liu et al. 2016). The number and types of soil fauna tended to aggregate at the surface and the vast majority of species and individuals were concentrated between 0 and 5 cm, perhaps because plant roots are mainly concentrated in the surface soils in a wetland and the ventilation is good in this layer. Other studies suggested that wetland plant roots were mainly distributed in the 0–10 cm soil layer (Russell 1977; Amiaud and Touzard 2004), so the living environment in this layer may be suitable for soil fauna. Indeed, deeper soils have limited permeability and are vulnerable to the effects of cyclical flooding (Baldwin, Egnotovich, and Clarke 2001; Capon and Brock 2006; Liu et al. 2015). In this study, while the soil fauna community diversity and density generally showed a gradual decrease with soil depth, the opposite occurred in some individual plots. Overall, however, there was clear variation in the vertical distribution of soil fauna, with obvious surface aggregation.

In this study, the density of the soil fauna community peaked in April 2010 at the long-term reed restoration lakeshore and natural reed lakeshore, and in November 2011 at the short-term reed restoration lakeshore. With the exception of the samples collected in February 2011, the soil fauna density was generally highest at the long-term reed restoration lakeshore, followed by the natural reed lakeshore, and was lowest at the short-term reed restoration lakeshore (Figure 2). The soil fauna density was higher at the long-term reed restoration lakeshore than at the short-term reed restoration lakeshore and natural reed lakeshore, regardless of the number of species or the number of individuals, perhaps reflecting the high vegetation coverage, relatively complex soil structure, and surface sediment layer at the long-term site. Vegetation litter is an important source of SOM that contributes to water conservation and helps stabilize the soil temperature stabilization. The soil fauna in this habitat type benefit from rich sources of food and a stable living environment (Yin et al. 2010; Korbel, Stephenson, and Hose 2019).

The ecosystem of the short-term reed restoration has a relatively simple structure, and the soil fauna living environment fluctuates greatly (Abdallah et al. 2018). Reproduction of soil fauna may be restricted at this site by the low quality and quantity of vegetation litter, and the periodic flooding (Ho et al. 2019). These conditions may also affect the amount and distribution of soil fauna, leading to low density and biological diversity of soil fauna (Fitoussi, Pen-Mouratov, and Steinberger 2016).

The number of species in natural reed wetlands, an important wetland ecosystem, is relatively low but generally very stable, because of the cyclical flooding (Davis, Austin, and Buhl 2006; Taihu River Basin Authority 2010). We found that the number of fauna in the natural reed lakeshore was less than that in the short-term reed restoration lakeshore in February 2011, perhaps because the reed wetlands were burnt during winter. The high temperature during the burning period may have caused the death of some soil fauna, and a corresponding decrease in the local density of soil fauna (Bengtsson 2002; Wardle et al. 2004; Franco et al. 2016).

Conclusion

We discovered a total of 93 groups of soil fauna in the reed-dominated wetlands along the shores of Lake Taihu. Specifically, we found 71, 51, and 63 groups at the long-term reed restoration lakeshore, short-term reed restoration lakeshore, and natural reed lakeshore, respectively. Enchytraeidae, Diplopoda, and Nematoda dominated the soil fauna at the long-term reed restoration lakeshore while Nematoda dominated at the short-term reed restoration lakeshore and natural reed lakeshore. In individual months, the soil fauna community densities in the long-term reed restoration lakeshore and natural reed lakeshore were not significantly different. The soil fauna density was lowest at the short-term reed restoration lakeshore, and highest at the long-term reed restoration lakeshore. The evenness was significantly different between the sites in August 2010, when it was higher at the long-term reed restoration lakeshore (H = 15.052, P < 0.05). There was no significant difference between the evenness at the different sites at the other sampling times. The other factor indicators (dominance, group number, and diversity indices) were not significantly different over the different sampling times, and there was little seasonal variation in the diversity of the soil fauna communities. The impact of the different indicators varied between the different restoration stages. The soil fauna tended to be aggregated in the surface soil and decreased with depth. The wetland restoration mainly affected the succession of the soil fauna groups over the long term, but had little effect over the short term. The density of soil fauna communities was generally highest in the long-term reed restoration site.
followed by the natural area, and was lowest in the short-term reed restoration site.

The changes in wetland soil fauna over a period of restoration can reflect how ecological functions are restored and can give useful insights into how soil fauna respond to wetland restoration. Soil fauna are therefore a useful indicator of wetland degradation and recovery. An indispensable component of wetland ecosystems, soil fauna have a role as consumers and disintegrators. When the numbers of beneficial soil fauna increase during wetland restoration, the reconstruction of ecological system function will improve and the process of wetland restoration will be more rapid. The relationships between wetland ecosystems, wetland restoration, and soil fauna need to be further studied, for example, through examining the ecological functions of key groups of soil fauna in wetland ecosystems, the functional mechanisms of soil fauna biodiversity, and the internal ecological processes of soil fauna and their ecological functions. Monitoring of wetland fauna over time can give insights into the processes and effects of biological habitat restoration, which can contribute to the development of robust management and recovery measures, and sound decision-making. Monitoring data can be stored in a database and can be used to support scientific and objective evaluations of wetland habitat restoration and reconstruction.

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