Spatial pattern of riparian plants along stream order among mountain rivers in China
Rong Sun, Xiaojie Luo, Xiangyu Meng and Yan Wang

ABSTRACT

The streams in a watershed form a hierarchical network system. From the perspective of the river continuum, this classification system is the result of gradual increase in traffic. This study analyzed the riparian species richness, diversity and environmental factors along a six-order hierarchical mountain river in the Donghe watershed, China. A total of 34 sampling sites were sampled to study the spatial distribution of riparian plants among different stream orders. The results showed:

Environmental factors among stream orders had significant differences. Among stream order, species richness showed remarkable differences. The species richness rose firstly and dropped afterwards except for tree species richness; tree species richness decreased while stream order increased. The same is true for shrub quadrat species richness. Shannon-Wiener diversity, Simpson dominance and Pielou uniformity showed significant difference among stream orders; Shannon-Wiener diversity rose firstly then dropped afterwards. For integrated environmental factors and community characteristics, we found the changes of stream orders had a significant impact on riparian habitats and riparian vegetation. Further analysis showed that riparian vegetation experienced different types and degrees of disturbance in different stream orders. This meant that a hierarchical management strategy should be applied to riparian vegetation management.

Key words | hierarchical management strategy, mountain river, riparian plants, stream order

INTRODUCTION

The riverside zone contains a series of lateral, vertical and longitudinal factors that change among streams, with hydrology considered to be the most important contributor to species richness (Sun et al. 2014; Papastergiadou et al. 2015). Riverside plants were defined as the vegetation adjacent to and affected by surface or ground water of perennial or ephemeral water bodies (Strom et al. 2011), which is a key element of riverine ecosystems, providing many ecological, aesthetic and economic benefits (Zaimes et al. 2011; Morrison & Stone 2015).

The riparian plant community is controlled by size and change of flow; if the flow pattern changes, the frequency and abundance of riparian plant species change (Strom et al. 2012; Lytle et al. 2017). When relating topographic variation to flooding frequency and duration, several authors have noted that changes in elevation of only a few meters or even centimeters can alter the composition, richness and diversity of species (Kupfer et al. 2010; Chatzinikolaou et al. 2011; Allredge & Moore 2014). This diversity is primarily derived from the survivors of disturbance and the invasion of new species that exploit disturbance gaps within riparian habitats created by flooding. The highest levels of plant diversity occur in the middle reaches of river valleys, where vegetation experiences moderate levels of flooding and this has been theoretically conceptualized in the intermediate disturbance hypothesis (Nilsson et al. 1989).

In general, the biodiversity of natural coastal areas is maintained under conditions of high spatial and temporal
variability, which reflected the environmental gradients along different spatial scales (Turner et al. 2004). In particular, the complexity of geomorphology and hydrology increased with the size of streams (Quinn & Wright-Stow 2008). As a result, the diversity of the plant community will increase with the stream order, especially the water dependent types (e.g. the habitats depend on groundwater at or near the surface of the habitat, such as fens and meadow types) (Dybkjær et al. 2012).

Plant community composition is defined by various factors, such as soils, water, human disturbance, landform, climate, and the formation of species that prevent the establishment and growth of species that cannot withstand environmental stresses (Kupfer et al. 2010). In fact, diversity of specific spatial scales is also constrained by the time scale, not just the local or regional ones (Renöfält & Nilsson 2008). It is critical to assess whether flow alterations on regulated rivers have impacted the riparian plant community (Loheide & Booth 2011).

Few studies have paid attention to riparian plants from source to estuary; Nilsson et al. (1994) analyzed the riparian species richness between main stream and tributaries. Given by the hierarchy of rivers in the complex watershed, the higher the grades the bigger the basin, and the more complex the rivers are the more tributaries they have (Khomo & Rogers 2009; Sun et al. 2017). Dybkjær et al. (2012) found that the abundance of alkaline fens and Molinia meadows in coastal areas varied with river size, while the abundance of moist meadow and wet herbaceous communities increased with the increase in stream order (first to fifth order). However, with respect to management, development and recovery of the rivers, it was important to correct attitudes towards the disturbances among stream orders. During the former studies about the classification of rivers and streams, riparian plants are often regarded as a qualitative description, but there were few studies with quantitative research on the characteristics of different levels of riparian plants.

This study is based on the hypothesis that the environmental factors and human disturbances to riparian zones controlled by stream order would cause the spatial patterns of riparian plants to change with stream order. The objectives are to: (1) measure the various environmental factors and human disturbances along the stream orders; (2) test the species richness and diversities along stream orders; and (3) provide a hierarchical management strategy for riparian vegetation management.

**MATERIALS AND METHODS**

**Study sites**

The Donghe stream rises from the Xuebaoshan mountain and empties into Pengxihe river in Kaixian county. The 96.7 km long stream is a high-gradient (>0.02 m/m), laterally confined, sixth-order river originating above 2,500 m elevation. Along the Donghe river, uplands belong to north semitropical evergreen broad-leaved forests consisting of mixed tree-, shrub- and grasslands. Vegetation of Donghe watershed is dominated by *Cyclobalanopsis glauca* (Thunberg) Oersted, *Viburnum erosum* Thunb., *Imperata cylindrica* (Linn.) Beauv., *Miscanthus sinensis* Anders., among others. The catchment area of the Donghe River is 1,426 km². Average stream flow is 40.8 m³/s and the peak discharge, which typically occurs in early June, averages 61.0 m³/s. The annual mean evaporation is 1,253.8 mm, which typically occurs in June to October, with a maximum and minimum of 1,716.4 mm and 795.7 mm, respectively.

**Field survey**

For this study, six orders of stream were compared. Considering the stream order and the accessibility, 34 sites were marked systematically on maps with four first order, five second order, seven third order, and six fourth, fifth and sixth order streams. Each site was 50 m long with a width between the highest and lowest water level riparian zone.

All vascular plant species were recorded and categorized in each site, by tree, shrub and herb. At each site three shrub plots of 5 m × 5 m and six herbal plots of 1 m × 1 m were investigated. At each quadrat, species name, average height, and coverage were recorded.

**Environmental data**

Seven environmental factors were recorded for testing the correlations among species diversity and site: altitude
et al. measured using a measuring tape. According to Nilsson
Among the orders, altitude (AL), riparian slope (RS), riparian width (RW), river width (RW), substrate types (ST), substrate heterogeneity (SH), and human disturbance (HD).

At each site the coordinate and altitude was recorded by GPS and the relief map. Following the International Geographical Union (IGU), a value of slope was weighted by inclinometer: 1 (0–2°), 2 (2–5°), 3 (5–15°), 4 (15–25°), 5 (25–35°), 6 (35–55°), and 7 (>55°). Riparian and river widths were measured using a measuring tape. According to Nilsson et al. (1989), substrate types and heterogeneity were based on substrate diameter values estimated by eye: boulders (–9.0), cobbles (–6.5), pebbles (–4.5), gravel (–2.0), sand (2.0), and clay (9.0). In order to include all substrate types, one additional type, bedrock, was arbitrarily given the respective diameter value of –12. Human disturbance refers to the effects of human activities, such as grazing, vegetation harvesting, industry and agriculture production, in the riparian zone, which was divided into three classes of intensity: high disturbance, moderate disturbance and light disturbance.

Data analysis

We analyzed the plant community among sites. Plant species richness, diversity, evenness and dominance were used.

The differences between environmental factors and plant community characters among stream orders were compared with the one-way analysis of variance (ANOVA). The relationship between environmental factors and species richness was calculated by Spearman’s method. Analyses were done using SPSS17.0.

RESULTS

Factor analysis

Among the orders, altitude ($P < 0.01$), riparian slope ($P < 0.01$), riparian width ($P < 0.01$), river width ($P < 0.01$), substrate heterogeneity ($P < 0.01$) and human disturbance ($P < 0.05$) showed significant differences while the substrate type did not show a significant difference ($P = 0.455$) (Table 1). The results showed that riparian width, human disturbance and river width increased and the riparian slopes and altitude decreased with increasing river order. With the stream order increasing, the substrate changed gradually from big particles taking the advantage to the small ones. For each order, based on the one-way ANOVA, altitude, riparian slope and human disturbance showed no significant difference between the first orders and the second ones, and no significant difference among the third, the fourth and the fifth ones, but the sixth orders showed significant difference from other orders. River width and substrate heterogeneity had a similar changing trend, in which the first, the fifth and the sixth orders had significant differences from each other while the second, the third and the fourth ones had no differences from each other and a significant difference from the sixth. As for the environmental factors, the first and the second orders of the river had similar conditions, the third, the fourth and the fifth had similar conditions and the sixth had its own characteristics.

Species richness along stream order

Along the orders, the species richness increased at first and then decreased (Figure 1) and there were significant differences between the orders ($F = 56.245$, $P < 0.01$). Among the orders, species richness was greater in the first orders than others ($P < 0.01$, Figure 1) and the fourth order was lower than others ($P < 0.01$, Figure 1). With the increment of river orders, the tree species richness increased and showed a significant difference between the orders ($F = 4.203$, $P < 0.01$, Figure 1). The shrub species richness also increased at first and then decreased in the same way as the species richness ($F = 7.434$, $P < 0.01$, Figure 1). The shrub quadrats showed a similar trend and the richness was greatest for third orders ($F = 16.194$, $P < 0.01$, Figure 1). The herb species richness and the herb quadrats showed a similar trend to the total species richness, which increased at first and then decreased (Figure 1) and showed a significant difference between orders in either sites ($F = 54.550$, $P < 0.01$, Figure 1) or quadrats ($F = 40.318$, $P < 0.01$).
Table 1 | ANOVA comparison of environmental factors among stream orders from first to sixth

<table>
<thead>
<tr>
<th>Stream order</th>
<th>First</th>
<th>Second</th>
<th>Third</th>
<th>Fourth</th>
<th>Fifth</th>
<th>Sixth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude (m)</td>
<td>1,252.75</td>
<td>1,112.40</td>
<td>866.86</td>
<td>898.67</td>
<td>790.29</td>
<td>480.00</td>
</tr>
<tr>
<td>Riparian slope</td>
<td>5.50</td>
<td>4.60</td>
<td>3.86</td>
<td>4.50</td>
<td>4.29</td>
<td>3.00</td>
</tr>
<tr>
<td>Riparian width (m)</td>
<td>5.25</td>
<td>8.40</td>
<td>13.00</td>
<td>16.50</td>
<td>22.00</td>
<td>28.83</td>
</tr>
<tr>
<td>River width (m)</td>
<td>5.25</td>
<td>16.20</td>
<td>41.29</td>
<td>45.67</td>
<td>52.43</td>
<td>121.50</td>
</tr>
<tr>
<td>Substrate type</td>
<td>3.25</td>
<td>3.60</td>
<td>3.71</td>
<td>4.00</td>
<td>4.14</td>
<td>3.50</td>
</tr>
<tr>
<td>Substrate heterogeneity</td>
<td>−3.55</td>
<td>−2.51</td>
<td>−1.89</td>
<td>−1.01</td>
<td>1.55</td>
<td>4.95</td>
</tr>
<tr>
<td>Human disturbance</td>
<td>1.25</td>
<td>1.40</td>
<td>2.43</td>
<td>2.33</td>
<td>2.43</td>
<td>2.67</td>
</tr>
</tbody>
</table>

Species diversity along stream order

For the shrubs, the diversities increased at first and then decreased along river orders, and showed significant difference among rivers ($F = 15.231, P < 0.01$). The evenness ($F = 5.673, P < 0.01$) and the dominance ($F = 11.951, P < 0.01$) of shrubs also showed significant difference among the rivers. The herbs had a similar changing trend to the shrubs in terms of either the species diversity ($F = 40.476, P < 0.01$), or the evenness ($F = 3.277, P < 0.05$) and the dominance ($F = 24.059, P < 0.01$) (Figure 2).
DISCUSSION

Vannote et al. (1980) found that with the increase in stream orders, many river parameters changed over a certain range (the first order to the sixth order). Gregory et al. (1991) also thought that the stream orders had important influence on fluvial geomorphology, the interaction of river and terrestrial, as well as riparian vegetation community characteristics. This study had similar results to these; that various environment factors, human disturbances and riparian plants exhibited significant differences among the stream orders, which supported the hypothesis that the environmental factors and human disturbances will be influenced by the stream orders, causing spatial patterns of riparian plant changes along the stream orders. Tang et al. (2004) also found that there were significant differences of altitude, river width and depth among stream orders at Xiangxi River. This paper found that physical factors changed with the stream orders and there were significant differences in chemical factors between stream orders. Brooks & Kyker-Snowman (2009) indicated that total runoff and sediment, water and sediment transport, catchment and sediment deposition had significant differences due to the stream orders, which affected the riparian characteristics (Table 1), river characteristics (Table 1; Nally et al. 2008), and river landscape (Huang et al. 2007), and then caused differences among the patterns of flood, water resources distribution and the transmission of inorganic and organic matter (Jin et al. 2010). This paper found that riparian width changed from 5.25 m to 28.83 m and the bank slope from 5.50 to 3.00 with the increase of the stream orders. The riparian zone became flatter with increasing stream order, with more human disturbance. Tang et al. (2004) found that river velocity decreased with increasing orders, and then the carrying capacity of the river sediment and organic matter decreased. The spatial pattern of particle size along rivers changed gradually from bigger to smaller (Teng et al. 2016). This study found that there were no
differences in substrate heterogeneity, but the dominant substrate types gradually changed from large particle size to small particle size with the increase in stream order.

In this study, riparian plant species diversity for stream orders showed significant difference (Figures 1 and 2), and the largest diversity appeared in the middle orders. The intermediate disturbance hypothesis indicated that the highest diversity index values were found under the intermediate disturbance and a large number of studies showed that the largest diversity of riparian plants was in the middle of rivers (Sun et al. 2012). In this study, the third orders had the biggest species richness among all the orders; this phenomenon was correlated with the third orders located at the middle altitude of the basin. Sun et al. (2012) found that the species richness was largest at the middle of the river. Tang et al. (2004) found that at a basin scale, the algal density, diversity index and primary productivity changed with the stream orders. In this study, the results showed significantly different species richness and diversity and the grades of rivers had significantly affected the spatial distribution of riparian plants at basin level. Species richness for trees was greatest for the first and the second orders which related to these rivers located at the high altitude, high slope and few human disturbances (Table 1) and implementation of the Natural Forest Resources Protection Project and the Returning Farmland to Forest Project to protect many trees. From the third to the sixth orders, the riparian zone experienced a different degree of development, and establishment of economic forestry reduced tree species diversity. From the species composition and field survey, the secondary shrubs and herbs composed the main plant communities, which were disturbed by humans but still maintained some natural characteristics.

According to the results of the drainage structure and field survey (Table 1), the stream orders were remarkably correlated to altitude – stream orders decreased with increasing altitude – which was similar to other studies on the spatial patterns of riparian plants changing with stream orders. Khomo & Rogers (2009) found that stream order controlled the river’s geomorphic and plant distribution, which had a significant effect on riparian plant composition. Combined with riparian plant floristic analysis and spatial analysis, from plant composition, species in low-grade streams (the first and the second grade) were influenced by the upland plant communities, the provenances of riparian plants. For example, in the riparian zone, the megaphanerophytes Cyclobalanopsis myrsinicefolia, Fagus longipetiolata, and Pinus armandii grew, which were the main vegetation types in Xuebaoshan Mountain. According to the field investigation, these areas were high altitude, high slope and only little human disturbance (Table 1); the riparian plants were influenced mainly by the river’s natural environment. The low-grade stream faced two issues of unstable water source and karst landform which affected the normal function of river ecosystems. The riparian plants from third and fourth grade streams were mainly shrubs and herbs with species from upstream and riparian heights (Nilsson et al. 2010) and were not similar to the first and second grade. Due to the higher altitude, bigger slope, and amount of water from the lower grade, a variety of riparian habitats was constructed which meant more species growth and reproduction. This study shows that the species richness and diversity were high at the third and the fourth orders (Figures 1 and 2). The composition and diversity of riparian plants were significantly affected by human disturbance (Nilsson et al. 1994). Mou et al. (2004) found that there was a positive correlation between stream orders and the frequency and intensity of human disturbance to the natural environment; with increasing disturbance, the plant coverage decreased.

In this study, much of the riparian zone was transformed to cultivated land and some ruderal and exotic species, such as Zea mays, Oryza sativa, Sesamum indicum, Cyperus alternifolius, and Mirabilis jalapa, grew in the fifth and sixth riparian zones. Nilsson et al. (1994) found that nearer to the estuary, ruderals constituted more and more of the riparian plants and the main stream had more ruderal plants than the tributaries. However, in this study, plenty of hygrophytes were found in the sixth grade rivers, which might be related to the impoundment of the Three Gorges Reservoir. The Donghe River was affected by the impoundment for a 20 km reach downstream, leading to a change in composition of the plant community (Sun et al. 2012). Paine & Ribic (2002) found that different management strategies for riparian zones would cause significant changes to the plant community composition and diversity and in this study, due to the different disturbances, both natural and...
human, the composition and diversity of riparian vegetation had significantly changed among stream orders (Figures 1 and 2) and then affected the ecological function of riparian and river ecosystems. According to Renöfält & Nilsson (2008) species richness and species composition were affected by the river continuum at macro-scale, by flood pulses at local scale and by human disturbances, topography, and other microhabitats at micro-scale. However, the management strategy of riparian vegetation should be changed when the stream orders change.

The study found that from the first to the sixth orders, river properties changed and the confounding factors also changed: for example, human disturbance increased with the gradual increase of stream order. The first and second orders were largely unaffected by human interference, while the sixth order received strong anthropogenic interference (Table 1). From the normalized difference vegetation index (NDVI), the riparian zone of the source of the river was mostly covered with trees and shrubs, the higher grade ones downstream with farmland and construction land. From the natural environment, the development of karst landform of the source stream resulted in no surface water flow in the river. On the other hand, global warming has brought a variety of hazards in recent years, such as temperature increase, precipitation changes and extreme weather, leading to changes in basins and streams, which had important effects on riparian vegetation (Palmer et al. 2008). The third and the fourth stream orders located in the middle of the basin, which received a large amount of water from the first and second order streams. These stream orders have relatively high elevation, large river gradient, and rich hydropower resources, therefore most of the hydropower in the Donghe River is located here and the main interference factors of these rivers were the cascade hydropower stations. According to the results of the composition of riparian plants and NDVI, the primary interference factors at the fifth and sixth stream orders were human disturbance, one was the change of land use in the riparian zone and the other was the impoundment of the Three Gorges Reservoir, which affected the Donghe River downstream through water level fluctuation.

Yu et al. (2009) figured out that the classification of river structure is basic work, which had important practical significance for river management and protection. Nally et al. (2008) found that the riparian width changed along stream orders and found that even in the same order the width also displayed significant differences due to the spatial position and geological conditions. Overall, the river hierarchy at a certain extent reflects the variation of the natural environment of the rivers. Khomo & Rogers (2009) also found that the stream order had fine control on river geomorphology and riparian vegetation, which could reflect the complexity of riparian vegetation. This paper found riparian environment factors and riparian vegetation were significantly different along the stream orders. Through a combination of field investigation and former studies, it was found that the types and the extent of outside interference on riparian plants were significantly different. This meant that for the management of riparian vegetation the spatial distribution law of riparian vegetation should be obeyed. The riparian vegetation should be managed according to the stream orders, i.e. using the hierarchical management strategy. Taking the Donghe River as an example, in the first and second stream orders, the riparian vegetation should be treated with the natural succession and some work on the protection and management of natural riparian vegetation should be done. For the third and the fourth orders, where the main influence factors were the damage to river continuity from hydropower development, their management should mainly include two aspects. First, the total catchment management model of water resources should be applied to allocate water resources to protect the natural riparian vegetation. Second, recovery and reconstruction work to damaged riparian vegetation should be strengthened and the water supply of downstream dams should be ensured to maintain the river’s natural disturbance regime to the riparian zone. For the fifth and the sixth orders, there are two main aspects to be managed. First, strengthening the fluctuating zone affected by the Three Gorges Reservoir using the appropriate plants to recover the zone. Second, for the reach that was mainly affected by the change of land use, recent work combined the construction of Chongqing Municipality with river forest engineering, vigorously creating riparian forest and enhancing the existing riparian forest protection and management, prohibiting the destruction of existing woodland.
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