Ecological Engineering 65 (2014) 147–158

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

A riverscape transect approach to studying and restoring river systems: A case study from southern China

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ARTICLE INFO

Article history:
Received 26 March 2013
Received in revised form 4 August 2013
Accepted 19 August 2013
Available online 11 October 2013

Keywords:
Stream ecology
River landscapes
Riverscape transect approach
Landscape pattern analysis
River restoration and management
China

ABSTRACT

Rivers provide critically important ecosystem services to society, and play an essential role in maintaining the structure, function, and integrity of landscapes in which the rivers reside. Better understanding of the patterns and processes in river systems requires a broader landscape approach that goes beyond the traditional linear and longitudinal focus. Such a landscape approach is especially important for effectively restoring and managing already damaged or degraded rivers around the world. Toward this end, here we develop a riverscape transect approach by adapting landscape gradient analysis with pattern metrics so as to quantify the longitudinal variations in the spatial pattern of the river-land complex from headwater to mouth. Two rivers systems in southern China were used to develop and demonstrate the approach. For each river, we first constructed a riverscape transect, consisting of a spatial series of overlapping neighborhood landscapes, then computed a selected set of landscape metrics, and finally depicted the longitudinal profile of riverscape pattern with relative location-based plots. Our results have shown that this riverscape transect approach is conceptually consistent with the increasingly prominent riverine landscape perspective and technically feasible with the aid of remote sensing data and landscape pattern analysis methods. In particular, landscape metrics, such as percentages of urban and native vegetation, patch density, and Shannon diversity, can be used to reveal important variations in riverscape structure along the river. These longitudinal profiles of riverscape pattern, used as spatial indicators, can help identify key socioeconomic drivers and ecological impacts of land use and land cover change in the watershed. Our study demonstrates that this riverscape transect approach can be a new and effective way of facilitating the planning and evaluation of river restoration and management efforts.

1. Introduction

The pattern of biodiversity and ecosystem processes along rivers has long drawn attention from researchers who study waterways (Bates, 1863; Allan, 2004). In particular, how headwater and downstream ecosystems vary in their structure and function has been a central question in stream ecology (Cummins, 1974; Statzner and Higler, 1985). To describe and explain the longitudinal variations in geophysical and biological attributes of lotic ecosystems, several hypotheses have been proposed. For example, the River Continuum Concept (RCC) describes the continuous changes in the geophysical features and associated biological variables of a river system from its headwater to mouth in a relatively predictable way (Vannote et al., 1980). In contrast, the Serial Discontinuity Concept (SDC) emphasizes that non-free flowing rivers, such as regulated streams (e.g., by dams), often have discontinuous changes in riverine geomorphology as well as biological populations and communities (Ward and Stanford, 1983). Later, the same authors of the SDC concept also proposed the Hyporheic Corridor Concept (HCC) that emphasizes the importance of the interwoven complexity generated by the interactions between vertical and lateral processes of the river (Stanford and Ward, 1993). The HCC hypothesis implies that predictable zonation of ground water communities and aquifer–riverine converging properties occurs within the hyporhetic zone (Stanford and Ward, 1993).

The Flood Pulse Concept (FPC) recognizes that flood pulses, produced by the interactions of geomorphological and hydrological conditions and varying in predictability and duration, play an important role in determining the structure, function, and dynamics of the major biota in the river–floodplain systems (Junk et al., 1989). Consistent with the FPC concept, Hynes (1975) stated that

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http://dx.doi.org/10.1016/j.ecoleng.2013.08.005

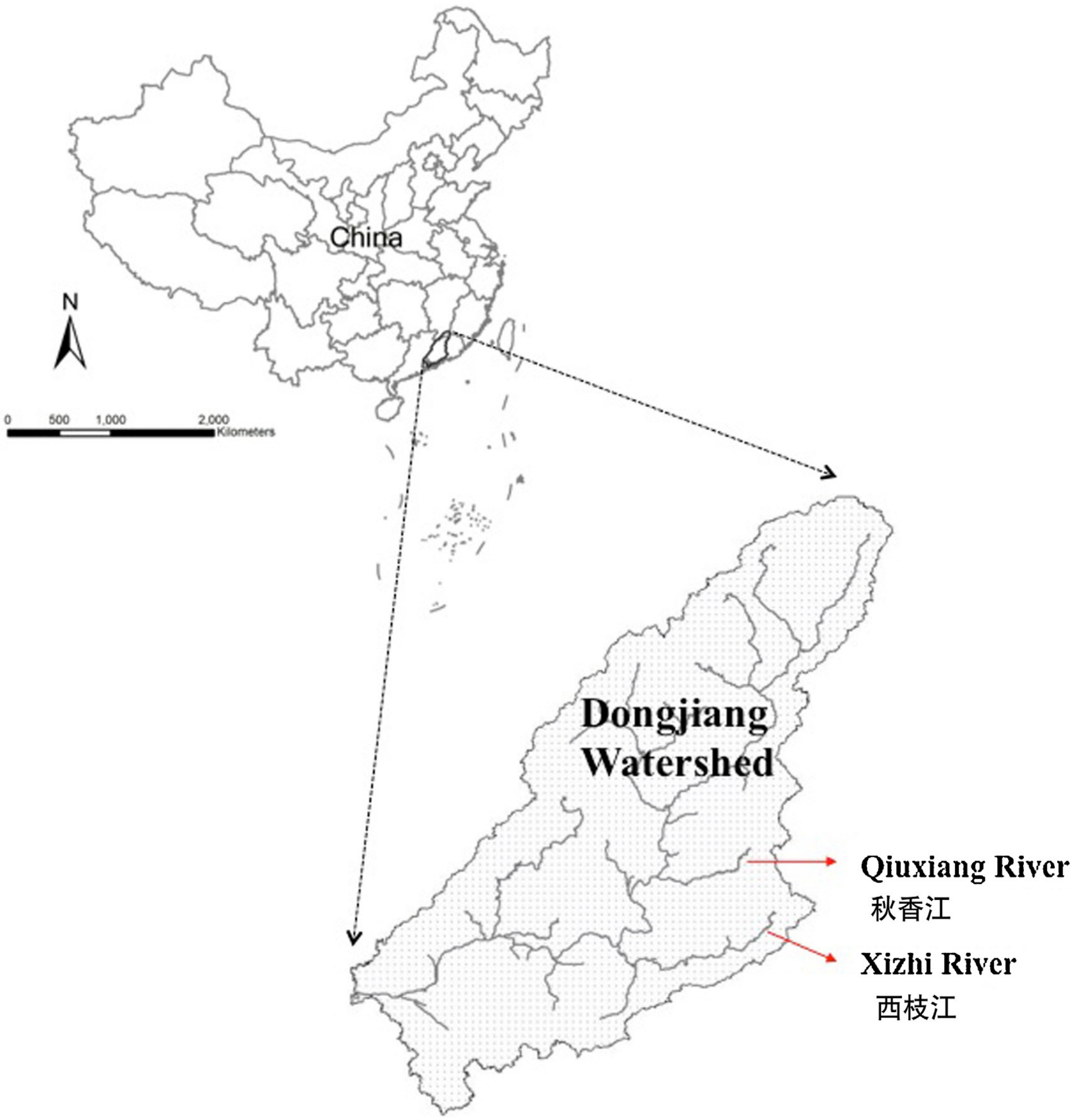

Fig. 1. Location map of the two study river systems, the Qiuxiang River and the Xizhi River, located within the Dongjiang (or Dong River) watershed, China.

"In every respect, the valley rules the stream." Apparently, FPC differs from both RCC and SDC because of its emphasis on the dynamic interaction between the main river channel and the landscapes sandwiching it. Nevertheless, all of the above-mentioned hypotheses focus on the longitudinal distribution of geophysical features and aquatic organisms along a river, a tradition that has been central in river research.

A number of stream ecologists have long observed that rivers are influenced by the surrounding terrestrial ecosystems (e.g., Leopold and Marchand, 1968; Cummins, 1974; Wallace et al., 1997). The concept of "riverscape" (or river landscape) was proposed in the 1960s when Leopold and Marchand (1968) used the term to describe the broad-scale physical, biological, and esthetic nature of rivers. However, it was not until the early 2000s that the concept of riverscape began to take on patch dynamic and landscape perspectives that consider a river system as a combination of broad-scale patterns of energy, matter, and habitat structure as well as locally discontinuous patches and zones (Wu and Loucks, 1995; Roth et al., 1996; Gergel et al., 2002; Poole, 2002; Ward et al., 2002a,b; Wiens, 2002; Allan, 2004; Kearns et al., 2005; Sullivan et al., 2007; Jones et al., 2010; Wu, 2013a). The past decade has witnessed a rapid increase in the application of landscape connectivity and metapopulation dynamics in river studies (e.g., Wu et al., 2003; Carbonneau et al., 2012; Eros et al., 2012; Segurado et al., 2013). Nonetheless, the landscape ecological approach to the study of rivers is still in its infancy, and much more research is needed to explore what it can offer to enhance our understanding of the ecology of rivers and our ability to restore and manage these ecosystems.

The goal of this study, therefore, was two-fold: to develop a landscape transect approach to systematically quantify the longitudinal variations in riverscape pattern for better understanding and managing river systems, and to demonstrate how this riverscape transect approach can be implemented technically for the purposes of stream research as well as river restoration and management.

2. Study area

To develop our riverscape transect approach, we chose two field sites, the Qiuxiang River and the Xizhi River, both of which are located in the Dongjiang Watershed, Guangdong Province, China (Fig. 1). The Qiuxiang River originates in Zijin County and flows into

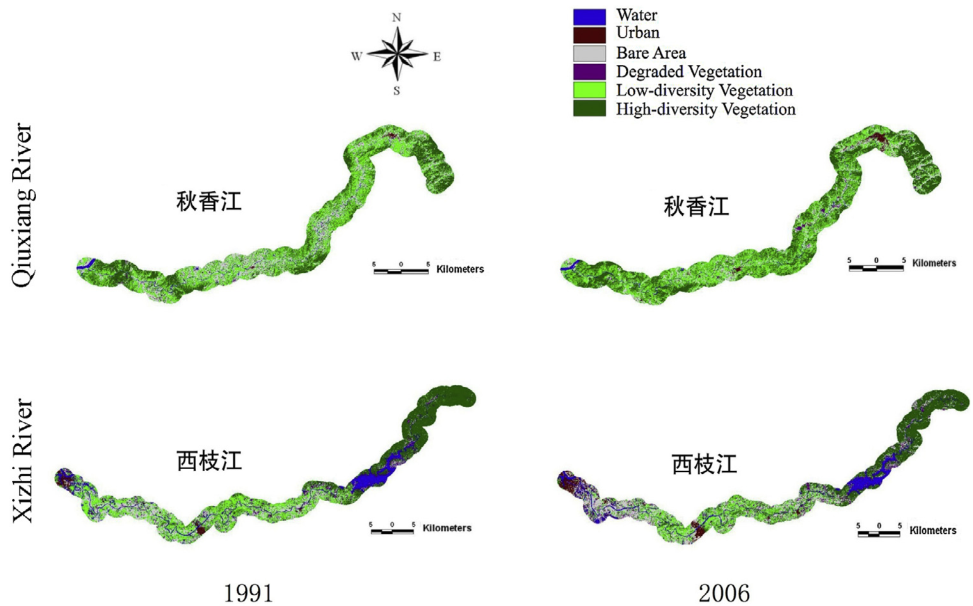

Fig. 2. Land cover classification maps of the two study river landscapes. The riverscape of each river was defined as the area encompassing the river channel and the buffer zone.

the Dongjiang River in Huiyang County. It is 134 km in length and 1669 km^2 in catchment area. The Xizhi River originates in Huidong County and flows into the Dongjiang River at Huizhou City. It is 190 km in length and 4103 km^2 in catchment area. The two river systems are similar in regional climate and socioeconomic settings, but differ in the details of topographic and land use conditions. Although we could have used just one of the two rivers to develop the riverscape transect approach, using both made our study more informative as we could compare and contrast the results for the two rivers. In addition, both rivers have been increasingly degraded due to human activities, and research is urgently needed for their restoration and management.

3. Materials and methods

3.1. Data acquisition and processing

TM images of the two study sites for the years of 1991 and 2006 were used to quantify river landscape patterns. From the SRTM (Shuttle Radar Topography Mission) data source (http://www2.jpl.nasa.gov/srtm/; pixel size: 90 m), we extracted the vector images of the Qiuxiang River and the Xizhi River using GIS software (ArcMap 9.3). These vector images were revised based on the river boundaries in the TM images. To delineate the river landscape, we created a buffer zone on both sides of the river channel with ArcMap. To accommodate different ecological processes and to examine possible scale effects, we considered three buffer widths: 1–3 km. In a multi-scale analysis of 73 wetlands in Canada, Houlahan and Findlay (2004) found that land use out to 2000–4000 m could significantly affected wetland water quality, but the effects tended to diminish beyond 3000 m. Because of the lack of information on the distance-based ecological effects of land use in our study region, we used Houlahan and Findlay's (2004) findings as a reference to set the range of our buffer widths.

The images of the buffer zones were then classified using a supervised classification method with ENVI 4.2, with six land cover types identified: water (rivers, reservoirs, and other water bodies), urban (cities, towns, and other impervious surfaces), bare land (beaches and un-vegetated areas), degraded vegetation (deforested areas), low-density vegetation (grasslands, croplands, and shrublands), and high-density vegetation (mainly native vegetation, including needle-leaved forest, broad-leaved forest, and mixed forests) (Fig. 2). The classification was groundtruthed using more than 30 evenly distributed ground control points. The overall accuracy of each land cover map was above 85%.

3.2. Landscape pattern metrics

The spatial pattern of a landscape can be quantified with landscape metrics at three levels: an individual patch, a class (patch type), and the entire landscape (including all patch types) (McGarigal and Marks, 1995). Some metrics are applicable at all the three levels (e.g., fractal dimension and other shape complexity measures) or at both the class and landscape levels (e.g., patch density, edge density, and connectivity measures), although their formulations and interpretations at each level are different. To quantify the changes in riverscape pattern along the study rivers – i.e., the riverscape transect profile – class-level and landscape-level metrics seem most appropriate. In particular, we selected three landscape pattern metrics: PLAND (percentage of landscape), PD (patch density), and SHDI (Shannon's Diversity Index), all of which have been used widely in quantifying changes in landscape pattern (Wu, 2004; Li et al., 2013). PLAND is a class-level metric, whereas PD and SHDI are landscape-level metrics. All these landscape indices were computed using the landscape pattern analysis software package, FRAGSTATS (http://www.umass.edu/landeco/research/fragstats/fragstats.html).

PLAND is the percentage of the landscape that is occupied by a particular land use and cover type (or patch type). PLAND is a simple and direct measure of landscape composition, which often has important ecological and environmental effects. For example, the relative amounts of green-spaces and impervious surfaces in an urban landscape significantly influence the distribution and intensity of urban heat islands (Buyantuyev and Wu, 2010), whereas the percentage of a human-dominated landscape that is covered by natural habitat is often found to be the most important determinant for biodiversity and ecosystem functions (Wu, 2009). In this study, we used PLAND to quantify the changes in two key land cover types (urban and native forest vegetation) that are important to the ecology of river systems in the region (Zhou et al., 2012).

PD is patch density, computed as the number of patches per square kilometer (i.e., 100 hectares). PD can be calculated for a given land cover type or for all land cover types in a landscape, which is a simple but reliable measure of fragmentation (Wu, 2004, 2009). SHDI is the Shannon's Diversity Index, a measure of land cover diversity which is a function of both the number of land cover types and their proportions in area (i.e., $\mathrm{SHDI} = -\sum_{i=1}^{n} p_i * \ln p_i$, where p_i is the proportion of the landscape occupied by land cover type i). Larger values of SHDI correspond to more diverse landscapes – i.e., landscapes with numerous land use types of similar proportions. The interpretation of SHDI may be complicated because its value is affected by several factors (Li and Reynolds, 1993; Li and Wu, 2004; Wu, 2004). Both PD and SHDI were computed at the landscape level, considering all the six land cover types. By so doing, we intended to capture the changes in the overall riverscape pattern from head to mouth.

3.3. *Characterizing longitudinal riverscape pattern with a transect approach*

To quantify the longitudinal variations in riverscape pattern, we took a "landscape transect" approach which is, conceptually, similar to the "urban–rural landscape gradient" approach in Luck and Wu (2002). This riverscape transect approach considers the spatial complex of the river channel and the upland as an integrative riverscape, and assumes that the spatiotemporal pattern of the riverscape affects, and is affected by, ecological processes operating in the river system. Technically, we implemented this approach using the "moving window" mode of FRAGSTATS. The first step was to create the "riverscape transect" which consisted of a spatial series of "neighborhood riverscapes" along the river. The so-called neighborhood riverscape here refers to the geographic area covered by the window. Because of the irregular shape of the river, we used a circular, instead of a square, window to minimize the inclusion of areas outside the river buffer zone. The distance between the origins of two adjacent neighborhood riverscapes was 30 m (corresponding to the spatial resolution of the TM data), and the radius of the circular window was varied from 1 to 2 and 3 km (corresponding to the three different buffer widths). With the moving window method, we generated about 4400 overlapping circular neighborhood riverscapes for Qiuxiang River, and about 6300 for Xizhi River. For simplicity, hereafter we refer to the river's main stem and its buffer on both side together as the "riverscape transect" which comprises a longitudinal spatial series of overlapping neighborhood riverscapes.

Once the riverscape transect was defined, the selected landscape metrics were then computed for all the neighborhood riverscapes (or circular windows) in 1991 and 2006, in order to characterize the longitudinal pattern of the two river systems. Altogether, the total number of the circular windows used for computing the landscape metrics was approximately 64,200 (i.e., (4400 + 6300) × 2 different years × 3 buffer widths). The origins of all the circular windows were located along the center of the river's main stem. The default order by which landscape metrics are calculated in Fragstats is from right to left and then from up to down. We wrote a script in Matlab so as rearrange the landscape metric values from the river head to the river mouth. To facilitate the comparison of riverscape patterns between the two rivers that have different lengths, we used "the relative location along the river" – the ratio of the distance from the river source to the total length of the river (ranging from 0 to 1) – to depict how the spatial pattern of the neighborhood riverscapes changed longitudinally from the headwater to the mouth.

A number of landscape metrics have been used to explore how riverine geomorphic structures may influence river habitats, including connectivity, habitat distributions, and patch-based spatial graphs (Gergel et al., 2002; Allan, 2004; Sullivan et al., 2007; Eros et al., 2012; Segurado et al., 2013). Some of these metrics, such as river width, depth, slope, and velocity, often are correlated with each other (Carbonneau et al., 2012). In this study, we are not proposing any new landscape or metrics per se, but rather we develop a moving window-based riverscape transect approach for quantifying the spatial pattern of river systems with any set of landscape metrics that are suitable for a given research or management purpose.

4. Results

4.1. *Riverscape transect profiles characterized by class-level metrics*

The riverscapes of our study sites each consisted of six land cover types (see detail in Section 3.1). Our earlier study of the Dongjiang River in the same region suggests that urbanization and native forest vegetation both have crucial impacts on the integrity of the river system (Zhou et al., 2012). Thus, here we focus on how the PLAND of two key land cover types – urbanized land and high-density vegetation (mainly native forests) – changed along the Qiuxiang River and the Xizhi River in 1991 and 2006. We also compare and contrast the results for three different buffer zones (i.e., 1–3 km). For clarity, we first describe the results of the 2-km buffer zone in detail and then explain those of 1- and 3-km buffer zones briefly by way of comparison.

For the Qiuxiang River and with the 2-km buffer zone, the proportion of urban land within the riverscape transect was generally smaller than 10% throughout the entire course of the river in 1991 and no larger than 30% in 2006 (Fig. 3a). For both years, the highest proportions of urban land occurred at relative locations of 10–20% and 65–75%, but the magnitude of urbanization in terms of spatial extent clearly elevated substantially from headwater to mouth in 2006 (Fig. 3a). Also with the 2-km buffer zone, the proportion of high-density vegetation cover was relatively high along the river for both years, and only a small portion of the riverscape had vegetation cover of less than 20% (Fig. 3b). While the general trend remained similar between the two years, vegetation cover increased appreciably in certain places within the upper, middle, and lower reaches.

For the Xizhi River and with the 2-km buffer zone, urban land cover was absent in the upper reach in 1991, and began to occur only at the relative locations of about 0.4 and above, with two peaks at 0.7 and near the river mouth (Fig. 4a). Overall, urban land cover increased substantially for the entire Xizhi riverscape transect – for example, urbanized area in the middle reach elevated from about 30% in 1991 to more than 50% in 2006. At the headwater of the Xizhi River, high-density vegetation was nearly 100% in 1991 and declined to 90% in 2006. In both years, vegetation cover within a neighborhood riverscape in the transect decreased rapidly from the source to the mouth of the river, approaching zero in the lower reach (Fig. 4b). For both Qiuxiang and Xizhi, urbanization along the rivers between 1991 and 2006 was primarily a result of expansion of previously urbanized areas. Also, locations where urban land was dominant tended to have lower amounts of native vegetation cover (Figs. 3a, b and 4a, b).

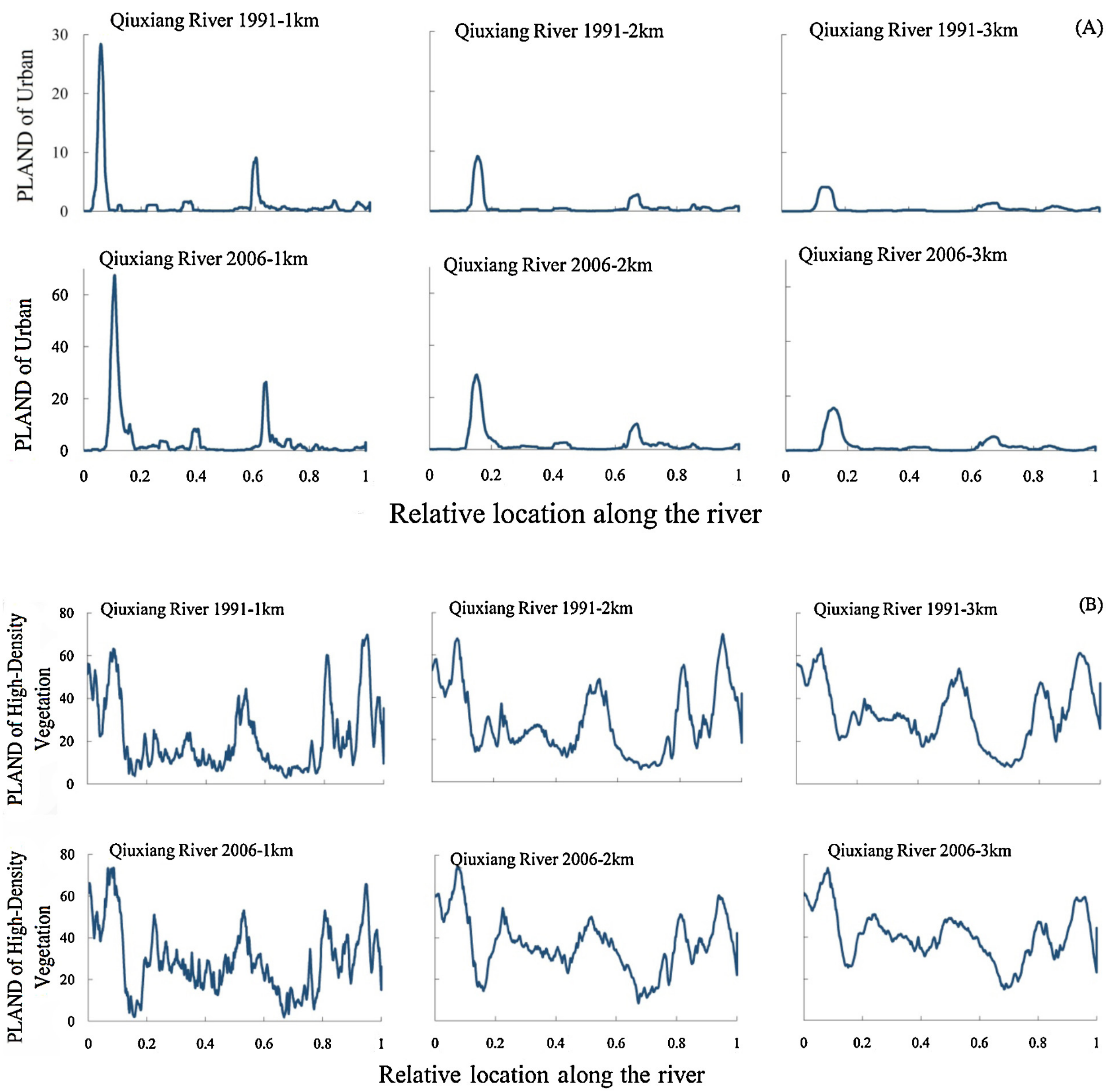

Fig. 3. Longitudinal variations in riverscape pattern along the Qiuxiang River in 1991 and 2006: area percentages (PLAND) of (a) urban land cover and (b) high-density vegetation (native forests). The landscape metrics were computed at three different buffer zone widths: 1–3 km. The relative location along the river is simply the ratio of the distance from the river source to the total length of the river.

How did changing the buffer zone width affect the riverscape transect profiles depicted with PLAND of urban and native forest land covers? Comparing the three plots across each row in Figs. 3 and 4 reveal that the effects of buffer zone widths were quite consistent for PLAND of urban land and native forest vegetation of both rivers in 1991 and 2006. Reducing the buffer zone width from 2 km to 1 km apparently resulted in more detailed fluctuations in metric values along the riverscape transect, whereas increasing the buffer zone width from 2 km to 3 km led to smoother riverscape profiles with respect to PLAND (Figs. 3 and 4). The average value of urban PLAND seemed to decrease with increasing the buffer zone width, but this decreasing trend was not as obvious for PLAND of native forest cover. It is clear, however, that the general pattern of changes in PLAND along the riverscape transect remained quite similar for the three different buffer zone widths.

4.2. *Riverscape transect profiles characterized by landscape-level metrics*

Here we again first focus on the results of the 2-km buffer zone width. The patch density of the six land cover types in combination fluctuated around a relative consistent mean value from the source to the mouth along the Qiuxiang River in 1991, but declined especially for the lower reach in 2006 (Fig. 5a). This indicates that the degree of landscape fragmentation varied, but remained within a comparable range in 1991, and reduced for much of the lower reach in 2006. The variations of land cover diversity along the Qiuxiang River, as indicated by SHDI, showed a similar trend, and did not differ substantially between the two years (Fig. 5b).

For the Xizhi River, in both 1991 and 2006 PD values increased rapidly in the upper reach, peaked in the middle reach, and then decreased in the lower reach (Fig. 6a). The longitudinal variations in

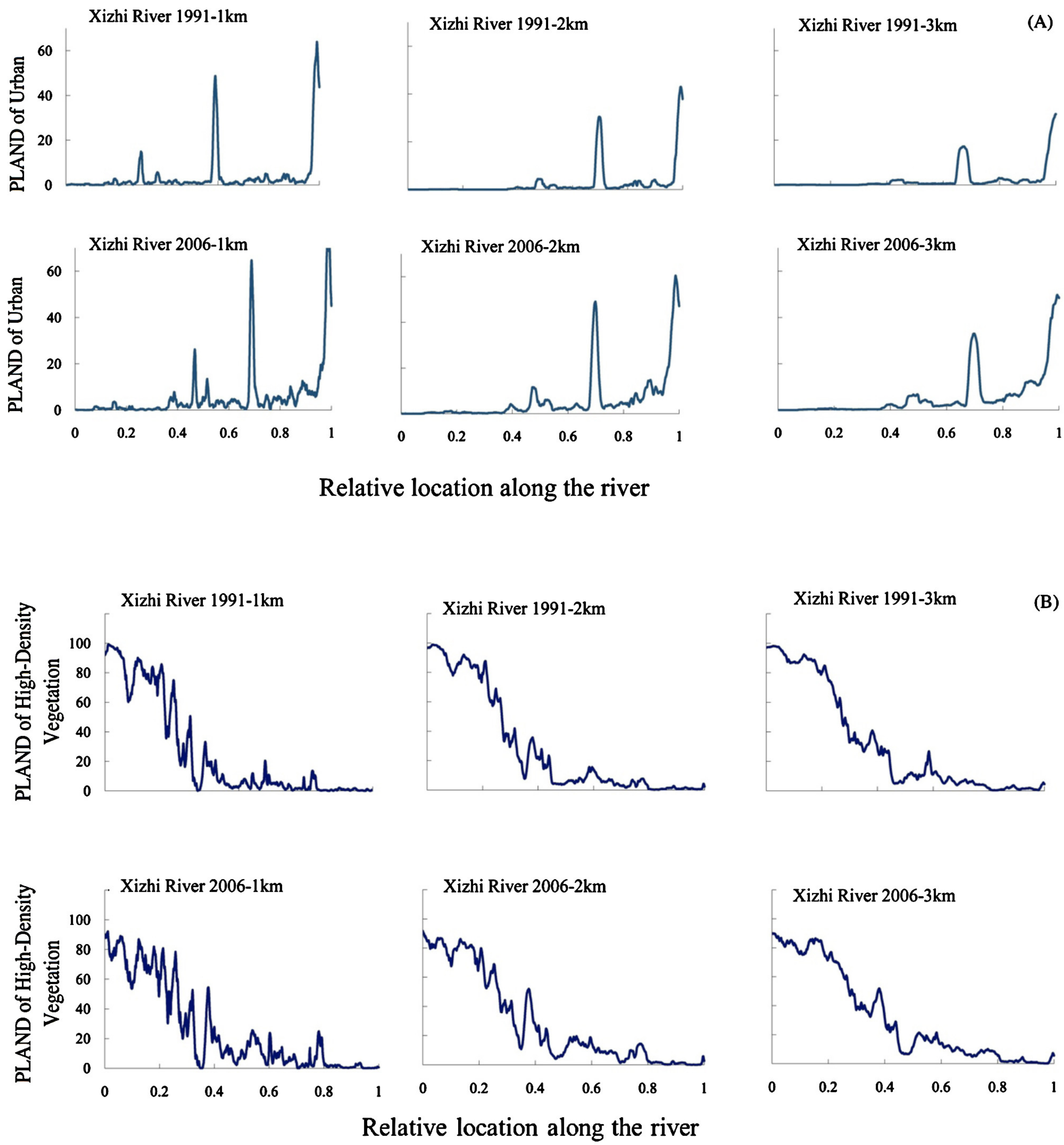

Fig. 4. Longitudinal variations in riverscape pattern along the Xizhi River in 1991 and 2006: area percentages (PLAND) of (a) urban land cover and (b) high-density vegetation (native forests). The landscape metrics were computed at three different buffer zone widths: 1–3 km. The relative location along the river is the ratio of the distance from the river source to the total length of the river.

SHDI showed a similar trend, indicating the variations in the degree of landscape fragmentation were highly correlated with those in the richness and the relative proportions of the existing land cover types (Fig. 6b). In general, the local riverscape pattern, as measured by PD and SHDI, had a much greater variability from headwater to mouth for the Qiuxiang River than for the Xizhi River.

How did changing the buffer zone width affect the results of PD and SHDI, and the riverscape transect profiles as a whole? Quite similarly to the situation with PLAND, the effects of changing the buffer zone width on PD and SHDI were consistent for both rivers and between the two years of analysis. Reducing the buffer zone width from 2 km to 1 km revealed more detailed fluctuations in metric values, whereas increasing the buffer zone width from 2 km to 3 km produced smoother riverscape profiles. However, the values of the two metrics (PD and SHDI) did not seem to change appreciably with the different buffer zone widths. Again, changing the buffer zone width did not alter the general pattern of the riverscape transect profiles depicted with PD and SHDI.

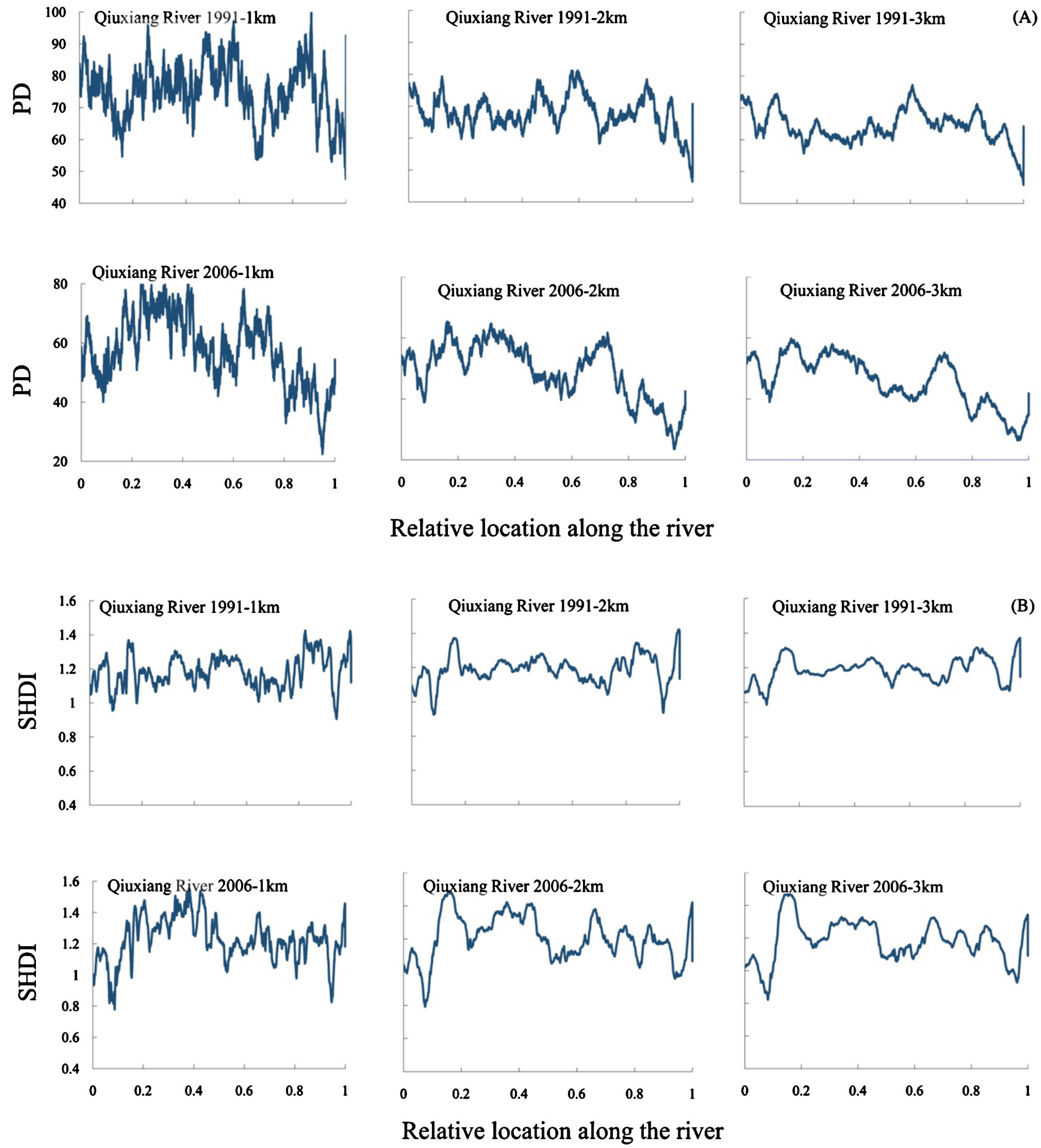

Fig. 5. Longitudinal variations in riverscape pattern along the Qiuxiang River in 1991 and 2006: (a) patch density (PD) and (b) land cover diversity (SHDI). The landscape metrics were computed at three different buffer zone widths: 1–3 km.

5. Discussion

5.1. Does riverscape transect pattern exhibit a continuous gradient from head to mouth?

As discussed in the Section 1, the River Continuum Concept asserts that the geophysical variables within a stream system exhibit a continuous gradient of conditions, including width, depth, velocity, flow volume, and temperature. If biotic properties of rivers conform structurally and functionally to kinetic energy dissipation patterns of the physical system, they may also change accordingly (Vannote et al., 1980). Does the head-to-mouth riverscape pattern, as measured by pattern metrics, also show a similar continuous gradient? Our study has clearly demonstrated that this is not the case. Instead, the values of riverscape pattern metrics showed non-linear forms of changes along the river, with various general trends

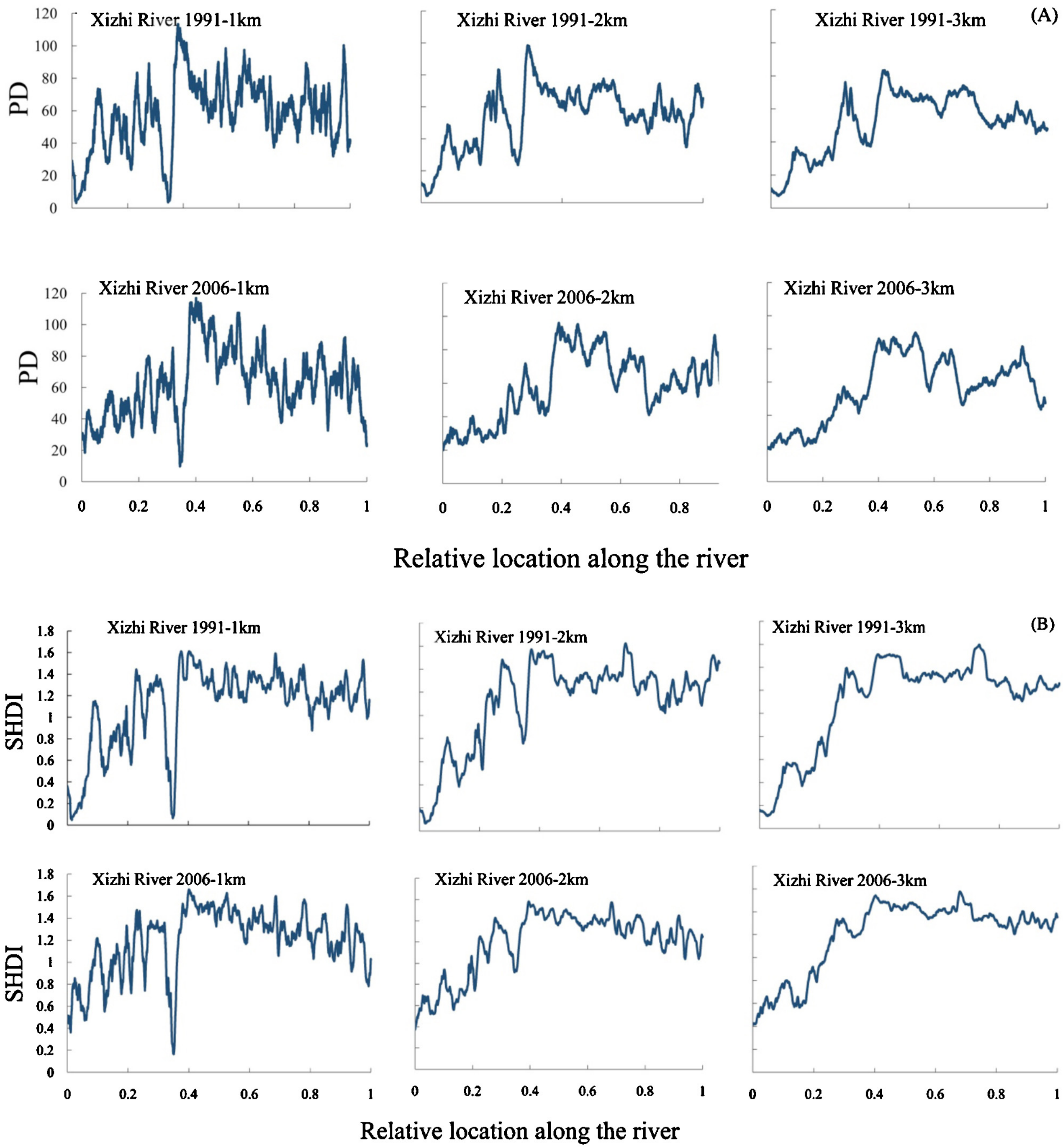

Fig. 6. Longitudinal variations in riverscape pattern along the Xizhi River in 1991 and 2006: (a) patch density (PD) and (b) land cover diversity (SHDI). The landscape metrics were computed at three different buffer zone widths: 1–3 km.

and detailed structures between different metrics. These features are further discussed below.

5.2. Three major characteristics of riverscape transect pattern profiles

By carefully examining the longitudinal changes in riverscape pattern metrics along the river, we have derived three major characteristics about the riverscape transect profiles of the two rivers in our study. These characteristics may be generally pertinent to rivers in different parts of the world although further studies are needed to confirm this speculation.

First, the longitudinal variations in riverscape pattern do not form a predictable gradient from the source to the mouth of a river, but rather a complex set of fluctuations that correspond, mainly, to geomorphological, climatic, and land use conditions. While similar environmental settings may result in resembling riverscape patterns, uncertainties in land use pattern, driven predominantly by socioeconomic processes, tend to unpredictably distort that similarity. In our study, none of the landscape metrics showed a linear gradient, and both local fluctuations and broad-scale trends appear to be nonlinear (Figs. 3–6). Conceptually, these riverscape transect patterns seem more compatible with the Flood Pulse Concept (Junk et al., 1989), lacking the high degree of predictability assumed in the other hypotheses of river systems that we discussed in Section 1.

Second, for the same river system, the observed longitudinal profile of riverscape pattern may differ when different landscape metrics are used (e.g., patch density, percentage of land covers, and diversity of land cover types in our study). Our study demonstrates that both landscape-level and class-level pattern metrics may be useful as they represent different aspects of landscape pattern. For example, PD and SHDI capture the overall degree of landscape fragmentation, while PLAND of urban and native forest land cover types carries important information for identifying potential causes for river degradation and for developing effective restoration measures. Thus, comparing and contrasting riverscape transect profiles revealed by different pattern metrics may lead to improved understanding of the geophysical and ecological conditions of the river system under study. In our study, for example, high-density vegetation cover and urban land cover seem to fluctuate in opposite directions along the river, suggesting that urban expansion may have been an important reason for the forest decline in the region. On the other hand, PD and SHDI showed similar longitudinal trends, implying that the riverscapes became more diverse in land cover types as they were increasingly fragmented. A comprehensive understanding of the patterns and processes in a riverine landscape, therefore, complementary multiple pattern metrics should be used. The choice of the metrics should be based on the research questions and objectives at hand (Li and Wu, 2004).

Third, the general pattern of riverscape profiles seems robust to changing buffer zone widths between 1 and 3 km, which represents a reasonable distance range probably relevant to most river ecosystem processes (Houlahan and Findlay, 2004). In other words, the riverscape transect profile of a river tends to retain its general shape when it is characterized by the same landscape metric, at the same spatial resolution, but with different buffer zone widths. However, it takes little imagination to figure out that further increasing or decreasing the buffer zone width will eventually and completely alter the shape of the riverscape transect profiles. This is essentially a form of scale effects that are associated with changing spatial extent (Wu, 2004). Although the spatial resolution (or grain size) in our study was fixed ($30\,m \times 30\,m$), sufficiently changing it will change the values of landscape metrics and thus riverscape profiles as well. The choice of the spatial resolution and extent in our analysis was based on the adequacy of capturing enough detail, and encompassing the major influencing domain, of the surrounding landscapes on both sides of the river.

Closely related to scale effects mentioned above, the thematic resolution of a map which reflects the number and identity of land use and land cover types will also affect the observed riverscape pattern profile of a river, based on our current knowledge of the behaviors of landscape metrics (Li and Wu, 2004; Bailey et al., 2007; Buyantuyev and Wu, 2007; Castilla et al., 2009). Thus, the criteria of land use and land cover classification should be set with the study objectives in mind. In our case, we identified six land cover types that are indicative of the ecological conditions of riparian vegetation and one of the greatest threats to rivers in China – urbanization. The sensitivity to thematic resolutions of data is not necessarily a problem in landscape pattern analysis, but it must be explicitly recognized and properly treated with ecological understanding (Li and Wu, 2004; Buyantuyev and Wu, 2007). In addition, as in most landscape transect-based studies, buffers of a certain width impose new boundaries which may affect the results of patch-based metrics. This boundary effect is usually negligible when the size of the window from which landscape metrics are computed is much larger than the grain size of the data (say, at least one order of magnitude). In our case, the ratio of the window size to the grain size is about 3490 (i.e., $(1000/30)^2\pi$) for the smallest buffer width (i.e., 1 km). Thus, it is safe to assume away any boundary effects here. The congruence in the general trends of riverscape transects for the three different buffer widths corroborates this claim.

The above observations are based only on two rivers, and their generality may thus be limited. With a different, multi-scale landscape approach, our previous study of the Dongjiang River also showed that the riverscape pattern had distinctive characteristics for different reaches, as did water quality measures (Zhou et al., 2012). More empirical studies are needed to better understand the longitudinal changes in riverscape patterns, and test whether the observed changing patterns of riparian landscapes have general ecological implications. Toward this end, the riverscape patterns reported here may serve as working hypotheses from which more research questions can be derived for different river systems.

5.3. What are the major drivers for the observed longitudinal riverscape patterns?

What factors account for the observed variations along the riverscape transect of the two study rivers? Climatic factors, such as temperature and precipitation, are well known to play an important role in determining the vegetation pattern of landscapes on broad scales, from regions to continents and the entire globe. Within our study region, however, climatic conditions are similar, and thus they were not likely a main factor for the observed longitudinal variations in riparian landscape pattern. It is also well documented that topography and geographical processes affect the spatial distribution patterns of land cover and biological organisms in riparian landscapes (Swanson et al., 1988; Roth et al., 1996; Ward et al., 2002a,b; Hofer et al., 2008; Piechnik et al., 2012). For both rivers in our study, the topography in the upper reach is quite hilly, while the lower reach is dominated by alluvial plains (Fig. 7). The upper reach poses logistical challenges to development, and has been mostly protected for conservation purposes. The flat topography and concentrated resources in the lower reach, on the other hand, renders attractive opportunities for agricultural and urban developments. Thus, in our study region geomorphology (especially topography) affected land use (particularly urbanization), and they both were major determinants of the observed riverscape patterns.

In general, humans have had profound impacts on the character and behavior of many, if not most, rivers around the world, and a number of these changes are irreversible (Fryirs and Brierley, 2009). Among the most severe human disturbances on rivers is urbanization, which usually results in direct destruction of vegetation and biological diversity, drastic changes in landscape composition and configuration, severe alterations of runoff pathways, and heavy pollutions from industrial sources and crowded populations. Historically, towns and cities have frequently been built along rivers for convenience and trade (Freeman et al., 2003). In our study region, this is also the case as urbanization increased substantially during 1991–2006 along both rivers under study (Figs. 2, 3a, and 4a). Our results show that urbanization was quite limited (less than 10%) in area within the 2-km buffer along the Qiuxiang River in 1991, but the urbanized land expanded considerably by 2006 (two to three times more).

For both Qiuxiang and Xizhi, the total native forest vegetation cover in 2006 was as high as, or even higher than, that in 1991 (Figs. 3b and 4b). However, it is rather obvious that, in both cases and for both years, the peaks of urban land mirrored the troughs

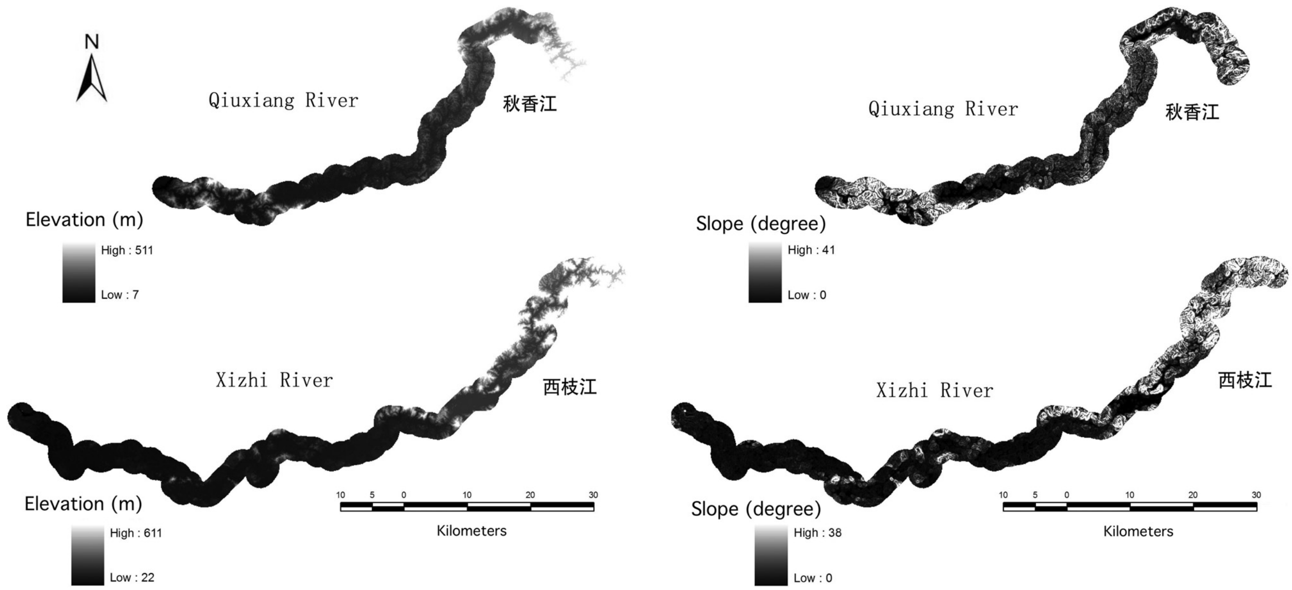

Fig. 7. Variations in elevation and slope along the Qiuxiang River and the Xizhi River.

of native vegetation cover along the river, suggesting that urbanization might have taken place at the expense of native vegetation. Also, high values of patch density and land cover diversity generally corresponded to high values of urban land cover, but to low values of native, high-density vegetation (Figs. 3–6). This suggests that urbanization created more patches and higher land cover diversity through introducing new types and altering the relative proportions of different types. However, extremely highly urbanized areas had lower patch density and land cover diversity as small urban patches coalesced into larger ones. These findings are generally consistent with the common trend reported in numerous urban landscape studies: during its early stages, urbanization fragments habitat, diversifies land cover types, and complicates landscape geometry (Luck and Wu, 2002; Wu et al., 2011). They also suggest that human activities have significantly affected the riverscape pattern and, thus likely, the ecosystem functions of the two rivers under study.

5.4. How can the riverscape transect approach help river restoration and management?

The restoration and management of river systems have long suffered from narrow scopes, inconsistent perspectives, and inadequate cross-disciplinary and cross-agency collaborations (Poff et al., 1997). As we mentioned in Section 1, however, this situation seems to have begun to change in the recent decades. A salient characteristic of the new ideas and approaches is the emphasis that the river and its surrounding land must be considered simultaneously as a riverscape in research and practice. This is essentially a landscape ecological perspective that has the river as the focal element of the landscape. As such, the composition and spatial arrangement of landscape constituents within and alongside the river channel all become clearly relevant to river restoration and management. In this view, to maintain the ecological integrity of a river system, the spatial pattern of the entire riverscape, including longitudinal connectivity and riparian buffer configuration, must be considered explicitly.

The riverscape transect approach, illustrated in this study, is based conceptually on such a landscape ecological perspective, and it may also serve as a powerful means to quantify changing riverscape patterns for a variety of restoration and management purposes. By constructing a longitudinal riverscape profile with a select set of landscape metrics, one can quantitatively assess the ecological conditions and land use-related drivers (or threats) over a river segment or the entire river system. For example, previous landscape ecological studies have shown that changes in nutrient export are related to forest landscape pattern, with complete forest cover greatly reducing nutrient export risk (Wickham et al., 2003, 2006). Each river may have a different riverscape transect profile, determined by a combination of geophysical (e.g., geomorphology and flow characteristics) and anthropogenic (e.g., land use and management practices) factors. Comparing and contrasting longitudinal riverscape profiles can help understand how the river and surrounding land interact and change. For example, bottlenecks for river connectivity and severely disturbed sections of the riverscape – places that require greater attention for restoration and stewardship – can be readily identified through the riverscape transect analysis. A riverscape transect profile based on the potential native landscape pattern that is devoid of human influences may serve as a reference for riverscape restoration at the scale of the entire course of the river.

The riverscape transect approach can be particularly useful for studying and improving the structure and function of riverine buffers when it is used as a diagnostic, monitoring, and evaluation method. Riparian buffers have been considered "a best management practice" (Piechnik et al., 2012) because they provide a high level of biodiversity and a variety of ecosystem services, including filtering out pollutants and other eroded materials from surface runoff. The ecological functions of riparian buffers that consist of natural land cover often extend far beyond their physical boundaries, and the degradation of these riparian systems due to human activities has caused increasing concerns (Baker et al., 2006; Jones et al., 2010). By changing the buffer zone width or using multiple buffer widths corresponding to important ecological processes, the riverscape transect approach can be used effectively to address both theoretical and practical questions concerning the structure and function of riparian buffers.

6. Conclusions

Rivers are linear structures, and research on rivers has historically focused on their longitudinal patterns of geophysical and biological properties, with inadequate attention to myriad influences from the adjacent terrestrial ecosystems. However, a landscape approach to studying and managing river systems – the riverscape approach – has become increasingly prominent during the recent decades, with numerous studies integrating rivers with their landscape context. A key first step in implementing a riverscape approach is to quantify the spatiotemporal pattern of the riverscape that encompasses upland systems surrounding the river, from which ecological processes can be better understood and management measures be designed. Toward this end, we have developed a riverscape transect approach to quantifying the longitudinal variations in the spatial pattern of the river-land complex from headwater to mouth, based on two river systems in southern China.

By computing landscape metrics through a series of overlapping moving windows along the headwater-to-mouth transect, this approach can produce detailed spatial signatures of riverscapes which can further be related to land change drivers and ecological processes. Not only can the riverscape transect approach be used for better understanding the longitudinal and horizontal dynamics of river landscapes, but also for effectively planning and monitoring river restoration and management efforts. A main advantage of the approach is to provide a spatially explicit, place-based framework based on which restoration and management priorities can be effectively identified across a river basin or a regional watershed. By integrating water and land that is increasingly dominated by human activities, the riverscape transect approach can contribute to the emerging science of landscape sustainability that highlights the importance of maintaining and improving ecosystem services in changing landscapes (Wu, 2013b). In addition, river restoration and management will not be sustainable unless key ecosystem services that rivers generate and influence are explicitly considered from the landscape sustainability perspective.

Acknowledgments

This work was supported by grants from National Natural Science Foundation of China (31300401 and 31030015), Guangdong Natural Science Foundation (S2012040007896), China's Postdoctoral Research Foundation (2012M521644), and Key Laboratory of Biodiversity Dynamics and Conservation of Guangdong Higher Education Institutes, Sun Yat-sen University. We are grateful to two anonymous reviewers for providing extremely valuable suggestions on an earlier version of this paper.

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