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Measuring the spatio-temporal variation of habitat isolation due to rapid urbanization: A case study of the Shenzhen River cross-boundary catchment, China

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ABSTRACT

With the expansion of human activities, human-dominated land cover conversion has become the most prominent cause of habitat fragmentation. Urbanization is currently one of the most significant factors driving land conversion and causing habitat fragmentation. Habitat isolation, as one major component of habitat fragmentation, is a dynamic process and complicated to evaluate and quantify. This paper intends to investigate habitat isolation due to rapid urbanization. Two new metrics, Urbanization Isolation Effect (*UIE*) and Habitat Isolation Degree (*HID*), are proposed to incorporate urban sprawl and population increase into the quantification of habitat isolation, and demonstrate its spatio-temporal variation. The Shenzhen River catchment, a cross-boundary region shared by Hong Kong and Shenzhen SEZ in China, has been used as a case study to demonstrate the effectiveness of these proposed metrics. The results show that (1) extensive land conversion to urban utility has occurred since 1988, especially on the Shenzhen side of the catchment; (2) the metrics of *UIE* and *HID* exhibited remarkable spatial and temporal variations in the whole catchment and also displayed a significant discrepancy between Hong Kong and Shenzhen; and (3) urban sprawl on the Shenzhen side exerted trans-boundary influences on habitats of the Hong Kong side. In summary, the two proposed metrics are proved to be effective in demonstrating the spatio-temporal variation of habitat isolation and its causes, as well as identifying the extent and intensity of the urbanization isolation effect. These metrics may be useful for regional planning and natural landscape conservation.

1. Introduction

Habitat fragmentation, describing the breaking up of continuous habitats (habitat isolation) and loss of habitats (Collinge, 1996; Jaeger, 2000; Wilcox & Murphy, 1985), is the major reason for the worldwide decrease in biodiversity and native species extinction crisis (Gonzalez, Mouquet, & Loreau, 2009; Steffan-Dewenter & Tscharntke, 1999; Wilcox & Murphy, 1985). With the expansion of human activities, land cover conversion resulting from human actions has become the most significant cause of habitat fragmentation (Collinge, 1996; Fischer & Lindenmayer, 2007; Kamusoko & Aniya, 2007). Large-scale land conversion leads to direct disruption of natural habitats, or results in indirect alteration of the structure, function and dynamics of ecosystems (Grimm et al., 2008), by changing hydrological processes and systems (Viglizzo et al., 2001), affecting climate at local and even regional scales (Diffenbaugh, 2009; Vitousek, Mooney, Lubchenco, & Melillo, 1997), and modifying energy flows and nutrient cycles (Viglizzo et al., 2001).

Urbanization, converting natural or semi-natural areas to urban utility, is currently one of the most significant drivers of land conversion (Long, Tang, Li, & Heilig, 2007). The extensive urban sprawl associated with population growth has led to serious fragmentation of natural habitats (Wilcox & Murphy, 1985), and the influence is believed to continue through the next decades (Alberti et al., 2007). China is not except from this process. Urban land expansion in China amounted to 8170 km^2 during the period 1990–2000 (Liu, Zhan, & Deng, 2005). Various negative impacts have been found in many cities in China during the past three decades (Du, Ottens, & Sliuzas, 2010). Urbanization has been, and will continue to be, a major factor driving land conversion and causing habitat fragmentation in China.

The question of how to measure and quantify habitat fragmentation has drawn much attention from various disciplines, such as landscape ecology, biodiversity conservation and landscape design and planning. Many landscape metrics have been

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developed to assess habitat fragmentation (Davidson, 1998; Frohn, 1998; Girvetz, Thorne, Berry, & Jaeger, 2008; Jaeger, 2000). Early developed metrics, such as edge length, interior area ratio, number of patches and average patch size can only reflect some limited aspects of fragmentation separately (Davidson, 1998). Recently, several new metrics, such as landscape division, splitting index and effective mesh size (Jaeger, 2000; Jaeger et al., 2008; Moser, Jaeger, Tappeiner, Tasser, & Eiselt, 2007), and Barrier Effect Index (Marulli & Mallarach, 2005), have been developed to be partially related to the whole ecological process of fragmentation, as well as to exhibit its spatial distribution. In order to fully understand habitat fragmentation, it is essential to evaluate and quantify habitat isolation.

Habitat isolation, in contrast to habitat loss, is a more complicated component involved in the fragmentation process. It refers to the process of the breaking up of continuous habitats independent of the reduction size. When habitat becomes discontinuous, the degree of habitat isolation is a key determinant, as movement of organisms among source patches is crucial to maintain species diversity (Crooks & Sanjayan, 2006; Magle, Theobald, & Crooks, 2009). Apart from habitats size, the spatial configuration (such as connectivity) of habitats across landscape has been considered as an important parameter in biological conservation strategies (Schumaker, 1996). Identifying suitable isolation metrics which could provide insight into how wildlife dispersal is influenced by the landscape elements is considered to be of great significance for future landscape modeling for protecting species biodiversity (Magle et al., 2009). However, the quantification of habitat isolation or its inverse, connectivity, is a very difficult task. Although numerous metrics have been developed, ranging from purely structural metrics (e.g. distance to the nearest neighbor) to complex potential and functional metrics (considering animal movement among patches), there is still no single isolation metric that has received widespread acceptance (Magle et al., 2009). In fact, habitat isolation does not depend only on the relationship among habitats, but also on the characteristics of the interjacent landscape, which may hinder (like roads and urban areas) or facilitate movements of species (Kindlmann & Burel, 2008). Thus, there is a need to develop metrics with relevant to the underlying isolation process and its causes.

Recently, the metric of Insulation Degree (*ID*) proposed by Su, Gu, Yang, Chen, and Zhen (2010) has shown some utility for the examination of the isolation effect exerted by interjacent urban areas. The concept originated from the Proximity Index, which is, however, insensitive to impermeable barriers such as a high density urban area (Gustafson & Parker, 1994). Based on the concept of *ID* (Su et al., 2010) the present paper proposes two new metrics which can integrate the urbanization process into the quantification of habitat isolation. To better illustrate the effectiveness of these new metrics, the Shenzhen River catchment, shared by the Hong Kong and the Shenzhen SEZ in South China, has been used as a case study. This catchment is a cross-boundary region with high spatial variation of landscape due to the different political frameworks and development scenarios that exist between Hong Kong and Shenzhen, especially over the past three decades. A catchment perspective is adopted in this study as it is considered as an optimal geographical area to analyze the effect of human activities on the environmental and ecological conditions (Sliva & Williams, 2001).

Our main objective is to address the following two questions: (1) what degree of habitat isolation is created during the urbanization process and which type of urban patches has caused such an isolation effect? (2) How does the habitat isolation vary across spatio-temporal scale and what are the major causes at the patch level? To accomplish the proposed objective, firstly the land cover change of the whole catchment over a period of twenty years is analyzed. Then the spatial variation of population increase is investigated for both Hong Kong and Shenzhen sides, as well as for each district of the two sides of the catchment. Different land cover types transformed to urban utility are also identified to reflect the disparity of ecological value loss during land conversion processes. The results of these are then integrated into the subsequent habitat isolation analysis. Finally, two newly developed metrics, namely Urbanization Isolation Effect (*UIE*) and Habitat Isolation Degree (*HID*), are calculated for measuring the isolation impact on important ecological habitats caused by urban sprawl and population increase.

2. Study area and data resources

2.1. Study area

The Shenzhen River catchment is located at the southeast part of the Pearl River Delta, in South China, between 113°52′E and 114°13′E and 22°23′N and 22°41′N (Fig. 1). The Shenzhen side, in the north, covers the districts of Luohu, Futian and Nanshan, as well as a small part of Buji town in the Longgang district, while the southern side mainly covers the Yuen Long and North Districts in the New Territories of Hong Kong. The total catchment area is approximately 726.72 km^2, of which the Shenzhen side occupies 412.95 km^2, equivalent to almost 57% of the whole catchment. An administrative boundary runs along the Shenzhen River separating the Hong Kong SAR and the Shenzhen SEZ. The Shenzhen River drains into Deep Bay, where the Futian National Mangrove Nature Reserve and the Mai Po and Inner Deep Bay Ramsar Site lie. Although the border-line between Hong Kong and Shenzhen has changed slightly after a river training project in 1998, in order to make the data comparable and consistent in this study, we assume that it remains the same as that in 1988. It should be noted that the boundary of the study area is larger than that conventionally used to define the Shenzhen River catchment in order to cover the whole Deep Bay catchment (see Fig. 1) so as to include all the important wetlands located at the estuarine area of the Shenzhen River.

A cross-border/boundary region is usually defined as a territorial unit that is composed by contiguous sub-national units of two or more nation states (Perkmann & Sum, 2002). Although the two sides of this catchment, the Hong Kong and the Shenzhen SEZ, are parts of China, they are administrated separately under the “One Country, Two Systems” policy. Hong Kong was, in fact, governed by the British Colonial Government before July 1997. This catchment can therefore be regarded as a cross-boundary region.

High spatial variation of land cover change and landscape fragmentation has occurred in this catchment, especially over past three decades. The Shenzhen side has experienced remarkably rapid development since the adoption of Economic Reform and Open Door Policy in China in the late 1970s. The landscape has, almost inevitably, been modified with the original fertile agrarian land now mostly replaced by a highly urbanized area. On the other hand, the Hong Kong side of the catchment remains largely rural with open areas, wetlands, woodlands, and some town villages. Although some areas on the Hong Kong side have been altered due to new town development and industrial land invasion, the speed and scale are much smaller than that of Shenzhen. Consequently, the whole catchment has experienced increasing environmental and ecological destruction in recent time. For example, extensive areas of intertidal mangroves, fishponds and gei wai (ponds for shrimp farming) have been lost or severely damaged because of human activities (Ren et al., in press; Zhang, Cai, Yuan, & Chen, 2004), and the water environment, as well as the sedimentation rate has also been changed due to the wetlands reclamation (Ren et al., in press). These have resulted in a substantial reduction of shrimp productivity and caused negative impacts on the aquatic ecosystem (Lau & Chu, 2000).

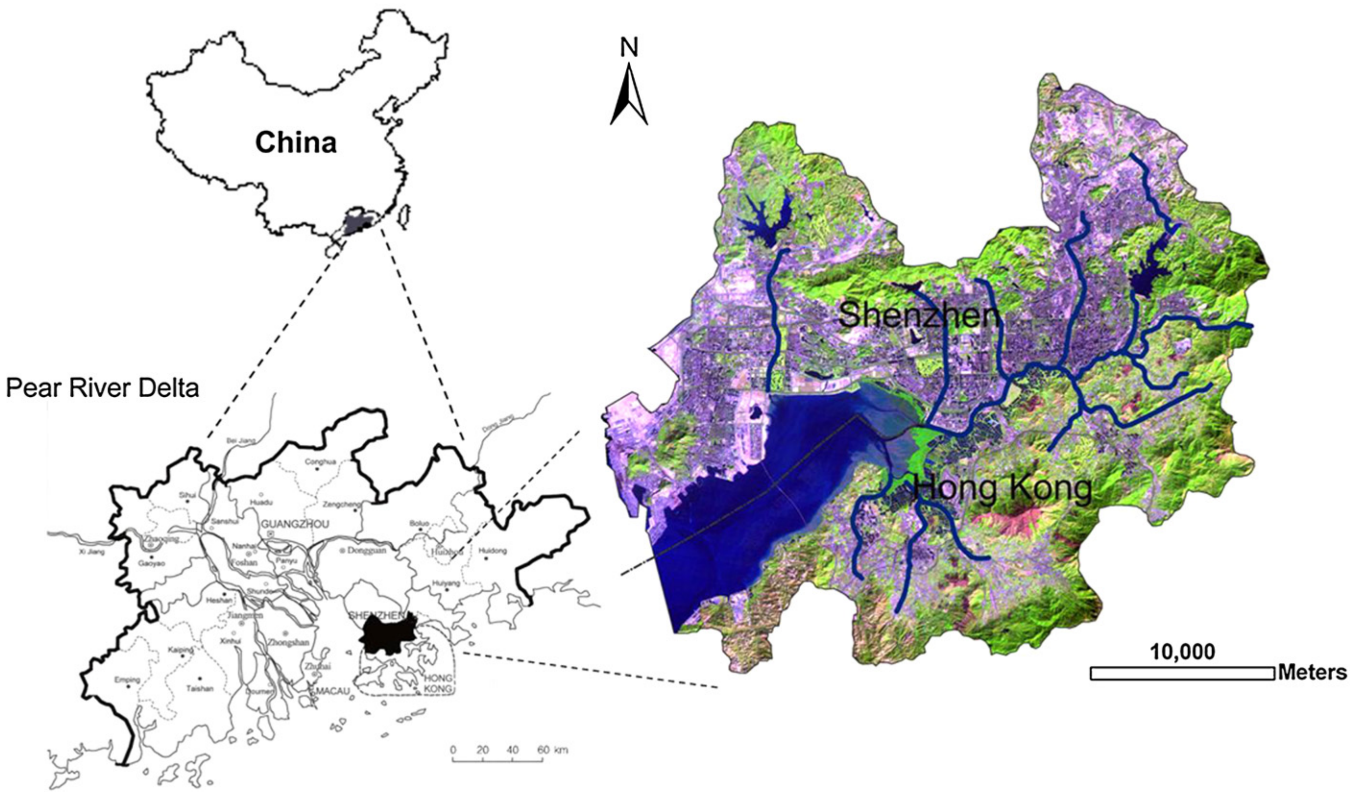

Fig. 1. Location of the study area.

2.2. Data resources

The primary land cover data used in this study were derived from the Landsat Thematic Mapper (TM) Imagery of different years, namely 1988, 1993, 1998, 2003 and 2008 (30 m $\times$ 30 m resolution, seven bands for each). Image processing and land use classification were performed using ERDAS IMAGINE software. In addition, 1:50,000 scale topographic maps were used for geometric correction under D_Krasovsky_1940 coordinate system with Albers projection. The mixed unsupervised and supervised classification method was used to obtain classified land cover maps. The ISODATA algorithm and Maximum Likelihood algorithm were employed in the unsupervised and supervised classification approach, respectively. To facilitate the comparison, the same classification system was adopted in this study which consists of seven land cover types, including cultivated land, forest, yuan land, urban built-up land, new development area, water area and road. Yuan land is a special landscape category in China which refers to land utilized for tree nursery and planting fruit trees. New development area refers to the land that has been recently bulldozed to make way for new construction activities (Yu & Ng, 2007). It is differentiated from urban built-up land as it shows a distinct characteristic in remote sensing images, and also implies different ecological impacts.

The accuracy of classification was evaluated using a confusion matrix. The sampling protocol included visual interpretation, field truthing, and higher resolution image comparison. At least 50 referenced points were selected for each class at the corresponding year. For cultivated land and yuan land, a considerable number of at least double points were selected in order to reduce the confusion of spectra characteristics for these two classes. For the 1988, 1993, 1998, and 2003 images, higher resolution color aerial photography and topographic maps taken in the corresponding years were used, and the overall accuracy are higher than 90%. For the 2008 image, field survey and GPS position were used to establish one-to-one relationship between the sampling sites and visual images. The overall accuracy for five images is 93.2%, 92.9%, 90.5%, 90.6%, and 94.2%, respectively. The Kappa Coefficient is 0.882, 0.881, 0.874, 0.852, and 0.891, respectively. It should be noted that relatively higher value was found for the 2008 classifications. This might be due to the greater field survey data with the help of GPS position.

In this paper the term habitats is referred to a series of important ecological habitats, which are identified based on several major studies, such as the Ecological Function Zoning Map of the Shenzhen Master Plan (2007–2020) by the Shenzhen Municipal Planning Bureau (2007), and the Final Habitat Map and Conservation Assessment Map of Hong Kong in 2006 (ERM, 2006). The present study focuses on assessing the impact of urbanization on large-scale important habitats, including important forest (mainly referring to Fung Shui forest, montane forest and lowland forest), internationally or nationally significant wetlands, major reservoirs and other important ecological corridors and sites. The loss of some smaller habitats during the land conversion process, such as scattered fish ponds, will also be integrated into later ecological value analysis. The spatial distribution of the identified habitats is shown in Fig. 2.

3. Methods

Two new metrics, Urbanization Isolation Effect (*UIE*) and Habitat Isolation Degree (*HID*), are proposed in this study. The *UIE* measures the isolation effect caused by newly transformed urban patches and population increase, and the *HID* is the total isolation degree of each important ecological habitat caused by its surrounding urban patches and population growth. They are designed to manifest the dynamic spatio-temporal interaction between habitat isolation and its causes. Based on the metric of *ID* (Su et al., 2010), new variables are introduced in these metrics to (1) examine the isolation effect caused by population increase, which is essential in the urbanization process, apart from urban sprawl and (2) integrate

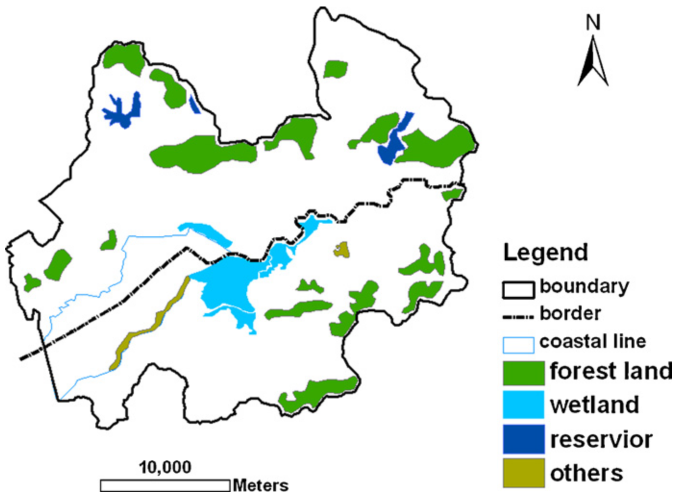

Fig. 2. Distribution of important ecological habitats.

the ecological value loss during the land conversion process, which could have a serious impact on habitat connectivity. Accordingly, the metrics of *UIE* and *HID* are defined as follows:

$$UIE_i = \frac{A_i}{A_{i\_buf}} \times \left(\frac{D_i}{\overline{D}}\right)^{-1} \times \frac{PD_i}{\overline{PD}} \times E_i$$

$$HID_j = \sum_{i}^{n} UIE_i$$

where UIE_i is the isolation effect of urban patch *i* and HID_j is the total isolation degree of important ecological habitat *j* caused by all urban patches within its buffer (with a certain radius). A_i and A_{i_buf} are, respectively, the area of urban patch *i* and the area of the buffer zone containing urban patch *i*. D_i is the distance from urban patch *i* to the nearest ecological habitat *j* and $\overline{D}$ (buffer radius) is the mean nearest distance of all urban patches to all habitats in the study area. PD_i is the population density of urban patch *i*, which is represented by the mean population density of the district where urban patch *i* is located. $\overline{PD}$ is the mean population density of the total study area. E_i is the degree of ecological value loss of transformed urban patch *i*. *n* is the number of urban patches within the buffer of each habitat. Each distance is defined as the cell center-to-cell center distance.

According to the above formulas, higher *UIE* and *HID* will lead to a higher isolation degree. They both increase with the growth in area of urban patches, population density and the degree of ecological value loss. On the other hand, they are negatively correlated to the distance between those urban patches and nearby habitats. Fig. 3 shows how isolation degree is influenced by the variables of area and distance.

Human population increase in an urban patch would pose impacts on nearby ecologically sensitive sites in the form of loss of biological diversity consequent upon changing the living environment of organism, such as the regional biogeochemistry and other invasive activities (Vitousek et al., 1997). Population density in different urban patches (PD_i), along with urban sprawl, is therefore taken into account in examining the isolation effect caused by both the intensity and extent of urbanization.

Additionally, the degree of ecological value loss (variable *E*) is included in the formulas to account for the different ecological value loss among the various land conversion processes. To quantify this variable, the concept of ecosystems services value proposed by Costanza et al. (1997) is adopted. However, considering the applicability to the current study area, the determination of this variable in the present study has been based on the research of Xie, Lu, Leng, Zheng, and Li (2003) and Li, Lu, and Wang (2007) on Chinese terrestrial ecosystems services value. Furthermore, in order to be closely related to habitat isolation, only the ecosystems services value for supporting the native life form was calculated, including climate regulation, water supply, soil formation and biodiversity conservation. For easy comparison among different scenarios, the values

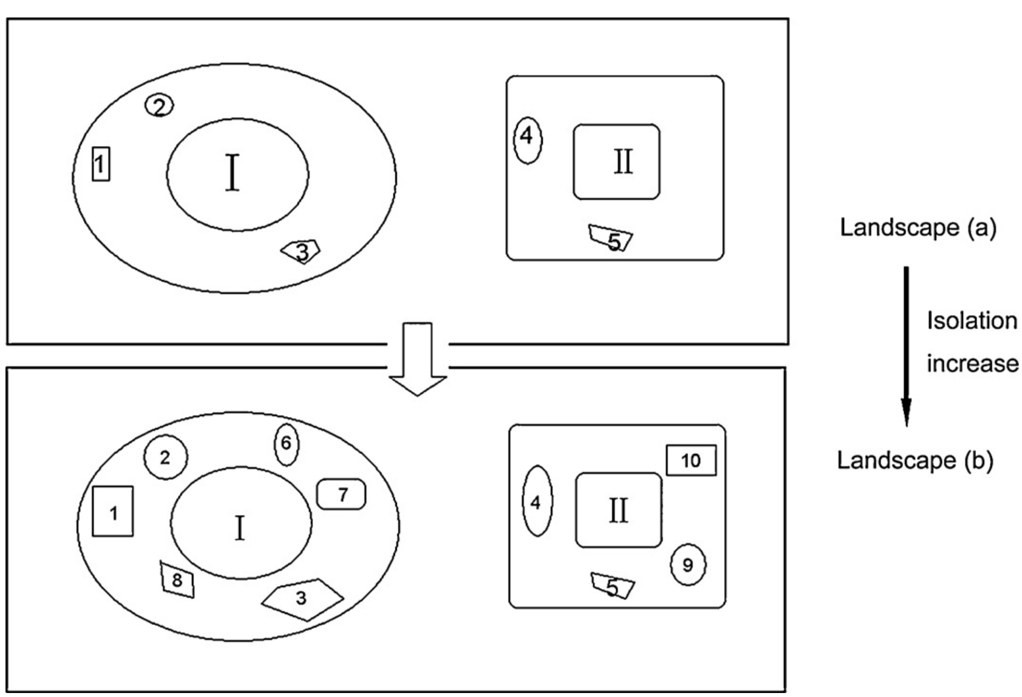

Fig. 3. Illustration of isolation increase process: this figure shows the isolated process from landscape (a) to (b), influenced by the variables of area and distance. Patches (I and II) are important habitats. Patches (1–10) are urban patches within the buffer of habitats. In landscape (a), there are only five urban patches surrounding the two habitats, and their areas are relatively small. After urban sprawl as in landscape (b), there are five more newly transformed urban patches and the previous ones also become larger and nearer (cell center-to-cell center distance) to the habitats. As a result, habitats (I and II) become more isolated.

Table 1
Different degrees of ecological value loss (E) during various land conversions.

Land cover types	Ecological service value	Land conversion types	Degree of ecological value loss
Urban built-upland	0	–	–
Cultivated land	15	Cultivated–urban	15
Forest	48	Forest–urban	48
Yuan land	36	Yuan–urban	36
Water area	100	Water–urban	100

were normalized to the range from 0 (urban built-up land) to 100 (water area) according to the method of min–max normalization. As a matter of fact, the value of habitat is species-specific and water area is not always ecologically more valuable than forests. However, the present study area is a river catchment, where the most important ecological sites are mainly composed of wetlands. While there is a large amount of forest lands, a big proportion of them consist of mixed shrub land and shrub-grass land. Thus, the ecological services value of water area is considered to be higher than that of forest lands in this catchment. Table 1 shows the degree of ecological value loss among different land conversion scenarios. The value of water–urban (referring to land conversion from water area to urban built-up land) is the largest, suggesting that the most serious ecological value loss takes place when a water area is transformed to urban land. On the other hand, the smallest effect occurs when cultivated land is converted to urban built-up land. The values of ecosystem services loss for forest–urban and yuan–urban conversions are both much larger than that for the cultivated–urban land conversion.

4. Results

4.1. Land cover change and urban sprawl

Land cover maps of the Shenzhen River catchment in the years 1988/1993/1998/2003/2008 are shown in Fig. 4. It must be noted that although large-scale expansion of the urban area and reduction of cultivated land in Shenzhen began in the early 1980s, Landsat TM data of the study area at that time is not available for the present study. Most areas of the catchment in 1988 were still undeveloped, and the landscape outside the urban center of Shenzhen was mainly composed of cultivated land, forest and water area. Compared to the small scale change on the Hong Kong side, the Shenzhen side experienced tremendous landscape change due to urban sprawl which was extensive. In addition, urban area on the Shenzhen side expanded mainly along the river and coast, while on the Hong Kong side, the urban areas were scattered at several locations in the catchment.

Table 2 shows the detailed information of land cover change within the study area over the two decades after 1988. Forest, water area and cultivated land were the dominant land cover classes in 1988, occupying 47.1, 23.0 and 16.4% of the total area, respectively. Urban built-up land only accounted for a small percentage at this time. However, between 1988 and 2008, cultivated land and water area lost about 90 km^2 and 50 km^2, respectively, and their relative proportion dropped by 12.4 and 7.0%, respectively. Forest, on the other hand, remained the dominant land cover in 2008 and had, in fact, grown slightly over the years. In contrast, urban built-up land increased to 140.10 km^2 in 2008, over six times more than that in 1988, and became one of the dominant land cover types in the whole catchment. The continuous increase of new development area was the reflection of the growing needs for urban development. The majority of this growth was concentrated on the Shenzhen side, while only a small proportion of urban expansion took place on the Hong Kong side.

4.2. Population increase

Population density varied at both spatial and temporal scales in this catchment from 1988 to 2008. There were significant increases on both sides of the catchment, with Shenzhen's figure being almost three times that of Hong Kong by 2008 (Fig. 5(a)). The total amount of population in the whole catchment in 2008 was about four times larger than that in 1988. Also, the incremental amount and rate were different between Hong Kong and Shenzhen, as well as among the different districts (Fig. 5(b)). The fastest growth occurred in the Futian District of Shenzhen while the slowest growth was in the North District of Hong Kong.

4.3. Land conversion to urban area

Land conversion from different land cover types to urban area was calculated in order to reflect the discrepancy of ecological value loss and subsequent isolation effect in different locations within the catchment. The study analyzed the urban built-up land transformation from cultivated land, forest, yuan land and water area from 1988 to 2008. Fig. 6 shows that the majority of land conversion was concentrated on the Shenzhen side, and cultivated land was the most dominant source in this land conversion process.

Table 3 shows the details of the land cover conversion from 1988 to 2008. The total area of land conversion from cultivated land, forest, yuan land and water area to urban built-up land amounted to 100.04 km^2, which accounted for 85.2% of the total increase in urban area and represented 13.8% of the total catchment area. Cultivated land accounted for more than half of the total, while forest and water area conversion contributed to about 43.2% of the total. This conversion of a large number of dispersed wildlife habitats would cause a serious impact to the connectivity of the existing important habitats and degrade the ecological value of the whole catchment.

Table 2
Land cover change of the whole catchment, 1988–2008.

Land cover types	1988		2008		% Change in land cover
	Area (km^2)	%	Area (km^2)	%	1988–2008
Cultivated land	119.35	16.4	29.20	4.0	−12.4
Yuan land	26.97	3.7	24.73	3.4	−0.3
Forest	342.16	47.1	346.41	47.7	0.6
Urban built-up land	22.71	3.1	140.10	19.3	16.2
New development area	21.99	3.0	38.95	5.4	2.4
Water area	166.90	23.0	116.15	16.0	−7.0
Road	26.65	3.7	31.19	4.3	0.6

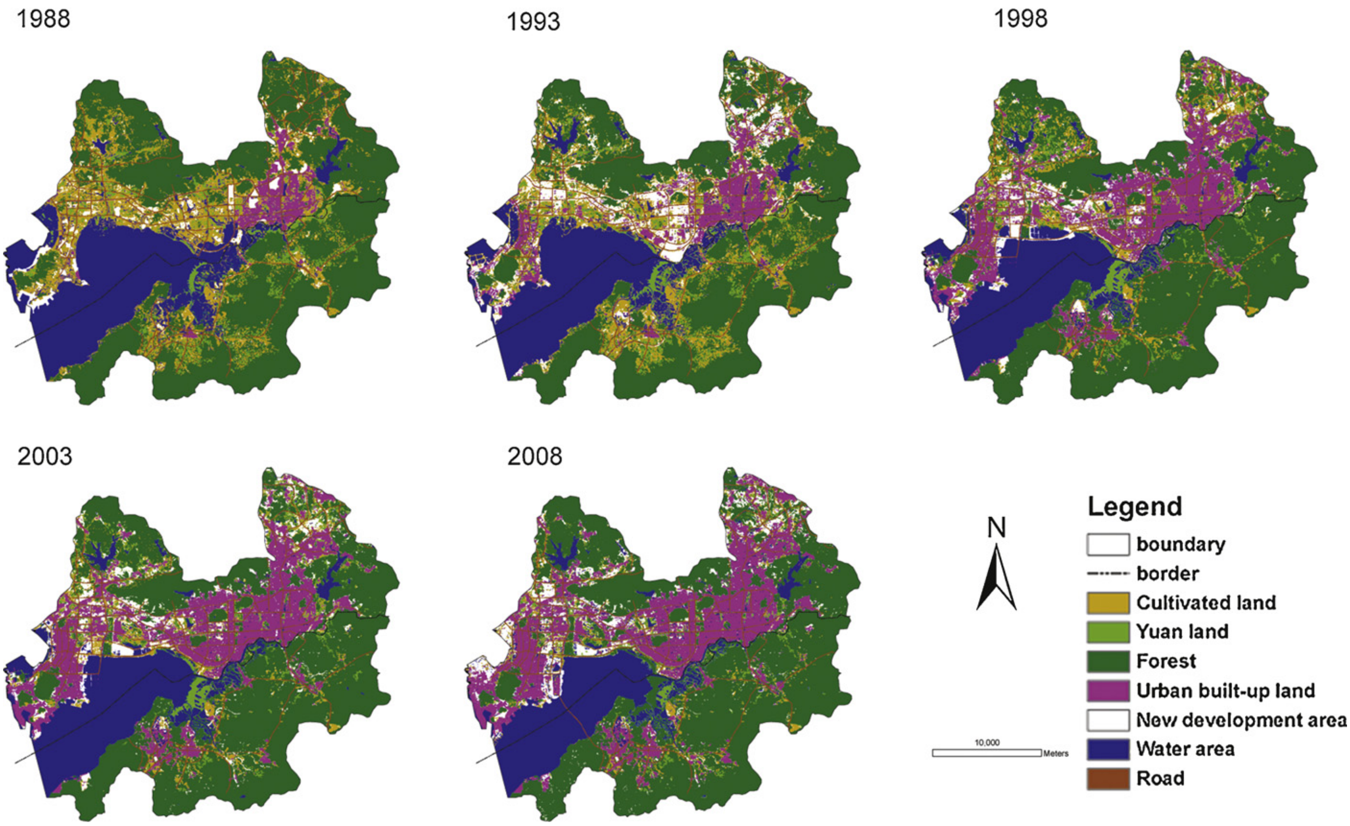

Fig. 4. Land cover maps of the whole catchment, 1988–2008.

Table 3
Land cover conversion from 1988 to 2008.

From class	To urban built-up land	
	Area (km^2)	%
Cultivated land	51.54	51.3
Forest	23.00	22.9
Water area	20.41	20.3
Yuan land	5.46	5.4
Total	100.40	100.0

4.4. Spatio-temporal variation of habitat isolation

Habitat isolation caused by urban sprawl and population increase in this catchment was calculated by two proposed metrics, the *UIE* and the *HID*. As the analysis focused on the cumulative impacts over different time periods based on the land cover of 1988, the results of periods 1988–1993, 1988–1998, 1988–2003 and 1988–2008, are presented in Tables 4 and 5 and Fig. 7. In Fig. 7, the values of the two metrics were classified into eight categories by the natural breaks method. They are dimensionless and can be easily compared.

It should be noted that while this study only analyzed the newly transformed urban patches within the buffer zones of habitats, these patches were in fact most directly and significantly relevant to habitat isolation, as they accounted for more than 88% of the total newly transformed urban patches in all the examined periods (Table 4).

4.4.1. Temporal variation of the UIE and the HID

Table 4 shows that the *UIE* had been rising over the whole study period. The maximam value of *UIE* had increased tremendouly from 1.65 to 28.53 from 1993 to 2008, and the mean value in 2008 was two times larger than that in 1993. This was caused by large-scale urban development in the study area. The sharp decrease of the buffer radius ($\bar{D}$) in 1998 indicates that a large number of newly transformed urban patches sprawled within the buffer zones of important habitats from 1993 to 1998. A slight increase of buffer radius from 1998 to 2008 suggests that urban patches

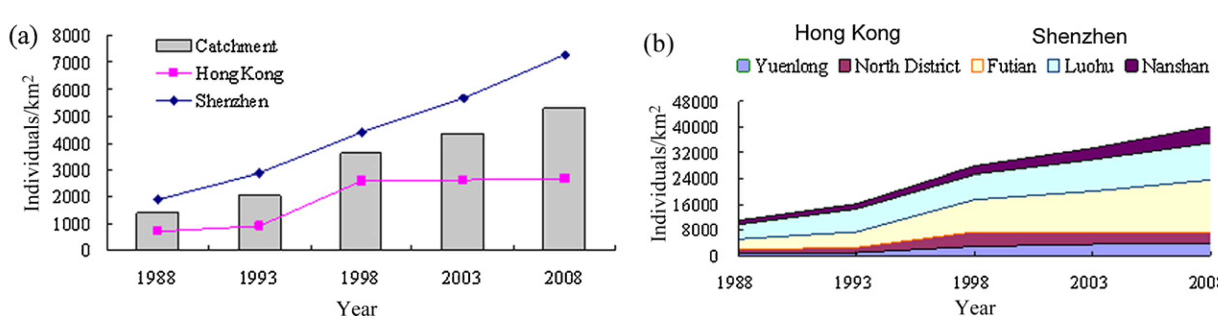

Fig. 5. Population density change, 1988–2008: (a) Hong Kong, Shenzhen and the whole catchment and (b) the different districts of the two sides.

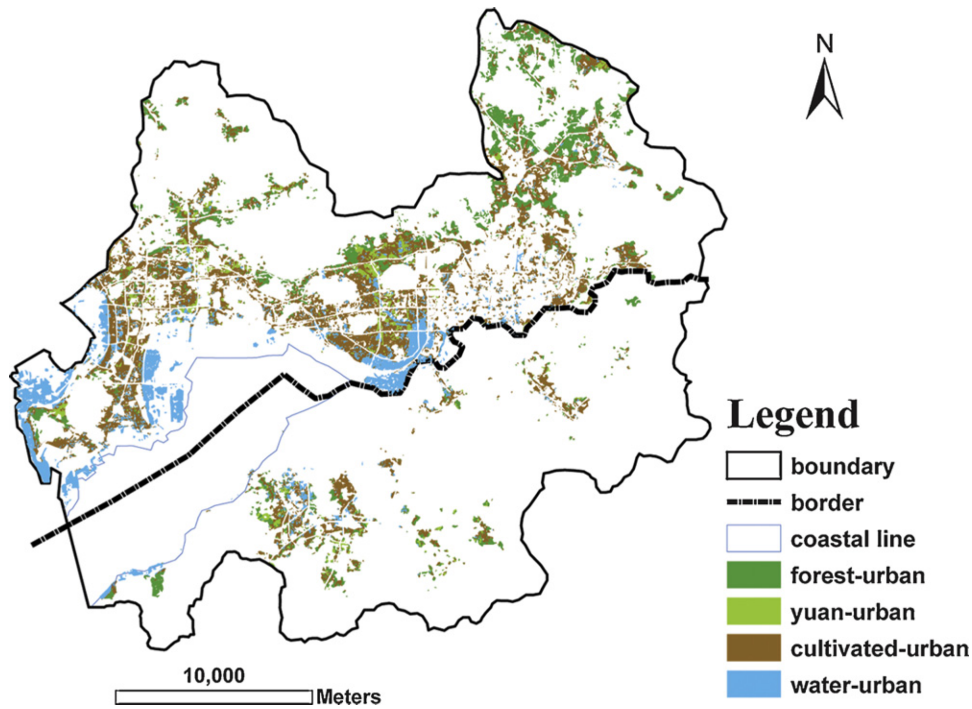

Fig. 6. Land conversion to urban built-up land, 1988–2008.

Table 4
Results of the *UIE* and the *HID*, baseline year 1988.

	1993	1998	2003	2008
Buffer radius ($\overline{D}$) (m)	3026	2948	2963	2986
Newly transformed urban land within buffer				
Area (km^2)	16.99	67.39	76.24	88.57
% of all converted urban land	91.9	88.0	88.1	88.2
UIE				
Maximum	1.65	5.45	10.57	28.53
Mean	0.013	0.012	0.018	0.028
Total	51.94	142.08	211.17	356.87
HID				
Maximum	9.60	25.98	37.10	81.41
Mean	2.00	5.46	8.12	13.73
Total	51.94	142.08	211.17	356.87

mainly spread on the fringe of the buffer zones of habitats during this period. Fig. 7 also shows that the most intensive urban sprawl near the important habitats occurred during the period 1993–1998.

The increase of *HID* implies that important habitats have become more and more isolated in this catchment since 1988. The mean value of *HID* was growing year by year, and the total value in 2008 was almost seven times larger than that in 1993 (Table 4). This was mainly resulted from the huge increase of urban land within the buffer area of habitats from 16.99 km^2 in 1993 to 88.57 km^2 in 2008. Moreover, the majority of these urban patches were converted from cultivated land, yuan land, forest and water area, which might have lost most of their ecological value during the process. The process also greatly reduced the connectivity among important ecologcial habitats and intensified the habitat isolation.

4.4.2. Spatial variation of the UIE and the HID

Fig. 7 shows the dynamic spatio-temporal interaction between habitat isolation and its causes. The most seriously affected habitats were concentrated mainly in the middle part of the catchment along the boundary between Hong Kong and Shenzhen, and in relatively smaller areas in the western and northeastern parts of Shenzhen. Compared to Hong Kong, the impact on the Shenzhen side was much more severe. Table 5 shows that there were significant differences between the two sides in terms of the maximum,

Table 5
Comparison of the *UIE* between Shenzhen and Hong Kong.

UIE	1988–1993		1988–1998		1988–2003		1988–2008	
	SZ	HK	SZ	HK	SZ	HK	SZ	HK
Maximum	1.65	0.05	5.45	0.53	10.57	1.04	28.53	1.07
Mean	0.013	0.003	0.014	0.004	0.021	0.005	0.034	0.005
Total	51.44	0.49	133.07	9.01	199.25	11.92	341.88	14.99
% of total	99.1	0.9	93.7	6.3	94.4	5.6	95.8	4.2

SZ, the Shenzhen side of the catchment; HK, the Hong Kong side of the catchment.

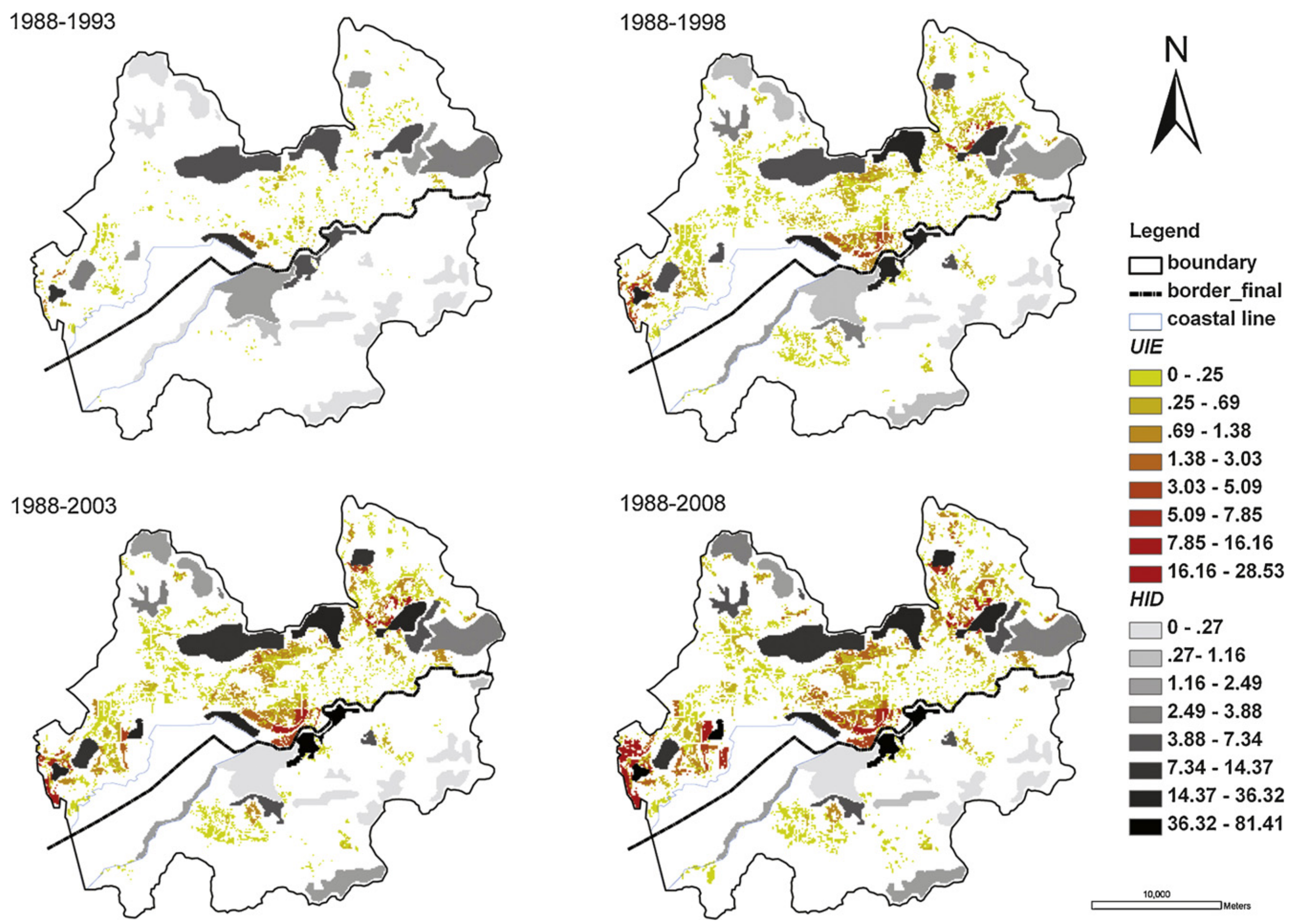

Fig. 7. Spatio-temporal variation of the *UIE* and the *HID*.

mean and total value of *UIE*. The mean value of *UIE* of the Shenzhen side was three to seven times larger than that of the Hong Kong side in all the examined periods. At least 93.7% of isolation effect within the catchment was contributed by the Shenzhen side. From the spatial distribution of *HID* on the Shenzhen side, as shown in Fig. 7, we can see that the Futian district (in the central part of Shenzhen) and the Luohu district (in the eastern part of Shenzhen) were most seriously affected between 1988 and 1993. The impact since 1998 then shifted to the Nanshan District (in the west of Shenzhen), mainly as a consequence of the substantial urban development and population increase there. The conversion of a large amount of water area to urban utility in this area might be another reason for the large increase of *HID*, as water area has the highest ecological service value among all the habitats in this study (Table 1). Besides, there was also a remarkable increase of *HID* in northeast Shenzhen after 1988, where some forests and reservoirs were located. Special attention should also be given to the habitats at the estuary of the Shenzhen River on the Shenzhen side, covering mainly the Futian National Mangrove Nature Reserve, as it was seriously affected during all periods.

On the Hong Kong side, although there were also some newly transformed urban patches scattered in the Yuen Long District, their isolation effects were much smaller in terms of their maximum, mean, and total value of *UIE* (Table 5). At most, only 6.3% of the total isolation effect within the catchment was caused by the Hong Kong side. However, severe impacts were unexpectedly found on some wetlands on the Hong Kong side along the Shenzhen River, especially since 1993, which made these wetlands the most seriously isolated habitat of the whole catchment. This was obviously not the result of urban sprawl on the Hong Kong side. The high *UIE* value north of these wetlands implies that the influence was largely created by the urban sprawl on the Shenzhen side across the boundary (Fig. 7).

5. Discussion

5.1. Habitat isolation and urbanization process

Landscape ecology aims at improving our understanding of the causes, dynamics and consequences of spatial heterogeneity (Turner, 2005). A large number of studies have demonstrated the impact of landscape fragmentation on biophysical elements such as biodiversity, wildlife habitats and configuration of natural lands (Fischer & Lindenmayer, 2007; Nagendra, Munroe, & Southworth, 2004). However, the causes and dynamics of fragmentation, as one core theme of landscape ecology, have not been well addressed. Habitat isolation, compared with habitat loss, is much more complex for evaluation. In order to adequately account for its causes and dynamics, the metrics should be related to not only the habitats but also the features of the surrounding matrix (Magle et al., 2009). It is therefore essential to determine which element, or elements, around important habitats would make significant impact upon them. In this paper, we propose that the isolation role of urban sprawl, associated with population growth, on surrounding habitats is an important factor to be considered. The urban sprawl and population increase are two important processes during urbanization. Comparatively, the process of urban sprawl is closely related to habitat isolation. It will not only directly occupy wildlife habitats, but also block or affect the connectivity among habitats by modifying the hydrological processes and changing energy flows and nutrient cycles. The construction of facilities and roads also play significant roles in influencing species movement. On the other hand, the increase of population will indirectly affect the habitat isolation by increasing disturbances to natural environment. Additionally, population growth is crucial in driving the urbanization process, especially in China. In western countries, current major urban growth and development tends to take place in small cities and at the urban fringe (Nagendra et al., 2004). However, in China large-scale urban sprawl associated with rapid population increase appears mainly in large cities, where natural habitats have been greatly encroached upon or fragmented. The present study attempts to use the two proposed metrics to illustrate the significant impact of urbanization on habitat isolation. In the case study of the Shenzhen River catchment, we found that both the extent (urban sprawl) and intensity (population density) of urbanization have had a tremendous influence on the degree and distribution of the isolation effect.

5.2. Implications of spatio-temporal analysis of habitat isolation

One of the improvements of the proposed metrics is their ability to demonstrate the spatio-temporal variation of habitat isolation and its associated causes. As illustrated in this case study, the metrics and the related spatial analysis reveal that the most seriously affected habitats were concentrated on the middle part of the catchment, and also that there was tremendous disparity of the isolation effect between Shenzhen and Hong Kong. The Shenzhen side contributed the overwhelming majority of the isolation effect. Moreover, the analysis shows that urban sprawl on the Shenzhen side could exert a serious influence on the habitats of the Hong Kong side. This could give us a valuable insight on how trans-boundary isolation was generated and what were the major causes. If this methodology were to become well integrated into cross-boundary planning studies, it will contribute to the development of a more holistic approach for ecological conservation and protection.

In addition, habitat isolation is a dynamic process, and temporal analysis is therefore important for describing and showing the trend of this process, especially in a region with continuous land cover change. In the case of the Shenzhen River catchment, temporal analysis indicates that both the *UIE* and the *HID* were rising over the whole study period and that the most serious influence was made during the period 1993–2008. This information can help identify major potential impact on habitats, and then it may be possible to adopt appropriate actions to mitigate the impact of urbanization on habitats. These findings can also be applied into future landscape design and planning. Especially in recent years the governments of both the Hong Kong and the Shenzhen SEZ are interested in developing the border area. We believe that by combining this approach with regional planning and strategic environmental assessment, it will help them to make sounder decisions regarding the development process.

5.3. Methodology assessment

5.3.1. Merits of the proposed metrics

Several studies have tried to relate landscape elements to natural landscape fragmentation (Marulli & Mallarach, 2005; Su et al., 2010). Our proposed metrics have successfully examined the dynamic spatio-temporal interaction between habitat isolation and its causes, especially at the patch level. These metrics not only consider the physical configuration of habitat patches (e.g. the distance between habitats), but also investigate the potential isolated impact to animal movement caused by the surrounding land cover change. Moreover, our proposed metrics attempt to integrate the influence of human factors into the measurement of habitat isolation. As such, it can provide planners with a wealth of information for impact analysis of land use planning scenarios. On the other hand, compared with the study of Su et al. (2010), who originally proposed the concept, our major contribution is in the incorporation of the ecological impact of the land conversion process (variable *E*) and the urbanization intensity (variable *PD*) into the new metrics. Both factors are essential to the understanding of the dynamics of land cover change and could help in effectively relating the metrics to ecological process.

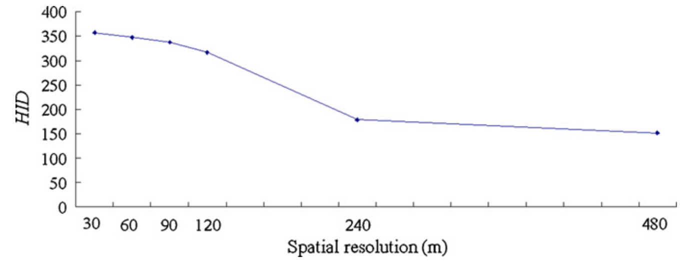

Fig. 8. The result of changing spatial resolution on the *HID* for the image in 2008.

5.3.2. Sensitivity analyses

As the performance of metrics may be affected by the scale of data used in the analysis (Frohn, 1998), we have tested the sensitivity of the proposed metric *HID* (i.e. the total of *UIE*) to different spatial resolutions of the data in the present study. In the test, the scores of *HID* are calculated based on data re-sampled in different pixel sizes, namely 60 m, 90 m, 120 m, 240 m and 480 m, from the Landsat Image of 2008. The results show that the scores of the metric remain at similar level between pixel size 30 m and 120 m (Fig. 8) but then drop significantly when pixel size is bigger than 120 m. This finding suggests that the same landscape may be interpreted as ‘high fragmentation’ at a finer resolution but as ‘low fragmentation’ at a coarser resolution (Frohn, 1998). It appears that the *HID* is not very sensitivity to image resolution within the pixel size of 120 m and the scores of the metrics are comparable among different spatial resolutions within this scale.

In addition to the above, two more simulation tests were conducted to investigate if the two new metrics are sensitive to various variables. In the first simulation, all variables are assumed to be constant except the variable of *PD* (population density), which is allowed to change according to the real data during the period of 1993–2008. The results show that both *HID* and *UIE* (maximum) increase at about the same rate as the growth of population density. In the second simulation, we assume that the population density is constant with time and attempt to investigate how the *HID* will change with the land cover transformation (urban sprawl). In this case, all the other variables are allowed to change as they will vary simultaneously during the process of land cover conversion. The test results also suggest that the *HID* is sensitive to the changes of these variables.

5.3.3. Limitations

There are several limitations of the present methodology. For easy calculation, the buffer radius in this study is defined as the mean nearest distance of all urban patches to all habitats of the whole study area. Ideally, the buffer radius should refer to the dispersal distance threshold of organisms, so that the metrics could be related to the ecological process more effectively. However, such a threshold is complicated and difficult to calculate in practice, as it varies among different species. This issue should be explored in a more comprehensive and integrated way in future studies. Besides, the isolation effect of urbanization on habitats is a complex process, and other relevant factors should be considered as far as possible. For example, while population density is supposed to be capable of reflecting the intensity of urbanization, the height and volume of buildings might also be appropriate and effective. However, due to the lack of detailed information these latter factors were not examined in the present study.

In addition, habitat isolation effect due to roads or other infrastructure network is a very important issue, but it is not investigated in the present study for two main reasons. Firstly, roads are hard to be detected on the TM images (30 m × 30 m pixels) presently used in this study. Secondly, the barrier effects of roads are determined by two major factors, namely road width and traffic density (Fahrig, Pedlar, Pope, Taylor, & Wegner, 1995; Forman & Alexander, 1998), but none of these data is available to us in the present study. The effects of road network should be considered in further study.

Finally, the sensitivity of metrics to classification scheme is another important issue needed to be addressed, as the variation of the classification number determines the scale of analysis which will then affect the evaluation of habitat isolation. A systematic sensitivity analysis based on more and fewer land cover types will be essential for evaluating the performance of the proposed metrics, and is recommended for further study based on a finer data source.

6. Conclusions

This paper investigated the dynamic process of habitat isolation due to rapid urban sprawl and population increase based on two proposed metrics, the *UIE* and the *HID*. A case study of the Shenzhen River cross-boundary catchment was employed to illustrate the effectiveness of the newly developed metrics. There are four major findings in the study: (1) a large number of cultivated land, forest and water area have been transformed to urban utility since 1988, especially on the Shenzhen side of the catchment; (2) The metrics of *UIE* and *HID* exhibited remarkable spatio-temporal variation in the catchment and also displayed tremendous discrepancy between Hong Kong and Shenzhen; (3) urban sprawl could exert a trans-boundary impact on habitat isolation in a border region; and (4) the two proposed metrics are proved to be effective in demonstrating the spatio-temporal variation of habitat isolation and its associated causes, as well as the extent and intensity of the urbanization isolation effect. These metrics may be useful for regional planning and natural landscape conservation.

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