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Assessing avian habitat fragmentation in urban areas of Hong Kong (Kowloon) at high spatial resolution using spectral unmixing

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ABSTRACT

The fragmentation, isolation and sparseness of vegetation in urban areas gives small patches of vegetation enhanced ecological value as habitat islands, compared with rural areas. Habitats as small as an individual tree may provide important landscape linkages across a densely urbanized city. Thus there is a need for micro-scale inventories of whole cities, which should incorporate not just biomass, but also vegetation of different life form, to support different habitat structural requirements. A combination of fine resolution multispectral satellite images from Ikonos, with the image processing technique of Linear Spectral Unmixing (LSU) permits the identification of different types of urban vegetation at sub-pixel level. Any fractional amount of grass and/or trees respectively within each 4 m Ikonos pixel can be identified.

To evaluate such fine scale inventory, least cost path (LCP) analysis was performed using pixel fractions representing micro-scale tree habitats. This study adopts an innovative approach by allocating variable weightings to the vegetation fraction amounts within each pixel, rather than to whole pixels. The result is a fuzzy friction surface, which constitutes a very high-resolution database for input to fuzzy querying and decision-making. The friction values represent species' preferences or tolerance levels, and may be varied according to the fraction amounts within a pixel. Automated mapping of least cost pathways over different friction surfaces produced different routes across the study area, the densely urbanized Kowloon Peninsula in Hong Kong. Comparison of the results with field data of bird sightings indicates the need for high detail in urban ecological analysis.

1. Introduction

The fragmented nature of wildlife habitats in modern cities (Bolger et al., 2000; Park and Lee, 2000; Huste and Boulinier, 2007) has prohibited sufficiently detailed inventories over whole cities, for comprehensive landscape ecological analysis. Not enough is known about how wildlife interacts with whole urban landscapes (Blair, 1996; Fernandez-Zuricic and Jokimaki, 2001; Melles et al., 2003), and Savard et al. (2000) recommend urban planners to inventory resources within a city at scales ranging from individual plants to the entire city. Until recently, field survey (e.g. Blair, 1996; Jokimaki, 1999) and manual air photo interpretation (e.g. Porter et al., 2001; Huste and Boulinier, 2007) have been the norm, and most research has concentrated on designated green areas such as parks (Jokimaki, 1999; Lock, 2000), pre-selected plots (Whitcomb, 1977; Opdam et al., 1984), or localized transects across urban–rural gradients (Blair, 1996; Clergeau et al., 1998; Lock, 2000), with only a few city-wide studies (Melles et al., 2003). Field surveys which have covered whole cities, in Hong Kong (Jim, 2004) and New York (Small and Lu, 2006), included only trees and were extremely manpower intensive. However Sodhi et al. (1999), in investigating bird usage of park connectors in urban Singapore observed that the designated routes with the most diverse bird communities were bordered by informal green space. This supports the (now long-standing) recognition that many urban unmanaged areas and informal green space are rich in species (Sukopp and Weiler, 1988; Wee and Corlett, 1986; Huste and Boulinier, 2007; Bino et al., 2008) and suggests that conserving recreational spaces and green areas, while ignoring non-designated vegetation is not the best approach. Thus an alternative for urban ecological surveys is to consider all existing habitats both natural and man-made, if extensive and detailed vegetation maps at life form level are available. However since urban vegetation is usually fragmented, previous low and medium resolution satellite sensors have been unable to resolve micro-habitats in densely urbanized areas. Such micro-habitats may have enhanced importance due to the oasis effect (Macarthur and Wilson, 1963; Wiens, 1994; Fernandez-Zuricic and Jokimaki, 2001) and their role in connectivity (Belisle, 2005). 'Fragmentation' is

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used in this study to refer to the heterogeneous and discontinuous patchwork of urban vegetation (which may include single, or rows of street trees, shrubs and grassy road verges, of both native and introduced species), rather than Fahrig's (2003) definition of patches derived from the breaking apart of a once continuous cover of natural vegetation accompanied by loss of habitat area.

This paper demonstrates that maps of vegetation life form produced from sub-pixel analysis of fine resolution satellite images are more effective and relevant for urban ecological analysis, than those produced from the previous generation of moderate resolution sensors, or from traditional 'per pixel' classifiers applied to fine resolution images. The 'soft' classification technique of Linear Spectral Unmixing (LSU) identifies the fractions (percentages) of grass and/or trees within a pixel (Nichol and Wong, 2007) and is thus able to generate very high-resolution fuzzy vegetation maps covering a whole city. These can be input directly as fuzzy surfaces (Lodwick, 2008) to spatial analysis routines for ecological landscape assessment, and automated least cost path (LCP) analysis (Berry, 1993; Ares et al., 2007) to depict functional pathways is given as an example in this study. The technique described provides a high-resolution raster database for landscape ecological modeling and hypothesis testing, which appears to be more relevant for understanding wildlife interactions, than previous scales of enquiry.

2. Techniques for urban vegetation survey

Sub-pixel analysis of fine resolution images such as Ikonos (Nichol and Wong, 2006) or Quickbird (Small and Lu, 2006) permits highly detailed and accurate vegetation mapping over a whole city. The image processing technique of Linear Spectral Unmixing (LSU) (Adams et al., 1986; Ridd, 1995; Phinn et al., 2002; Nichol and Wong, 2007) is a soft classifier, which avoids the mixed pixel problem of hard classifiers such as maximum likelihood (MLC) by computing the proportions of cover types (endmembers) within a pixel, and does not allocate pixels to a single class. The outputs from LSU are fraction images whose pixel values represent the percentage of a given cover type within a pixel. Nichol and Wong (2007) demonstrated that trees and grassy surfaces can be recognized and mapped as distinct pixel fractions using the uniquely high spatial, spectral and radiometric properties of the Ikonos satellite sensor. Where the pixel size is $4\,m \times 4\,m$, as with Ikonos, a 20% tree fraction represents one or more micro-habitats totaling $3.2\,m^2$ in size within that $4\,m \times 4\,m$ area. Furthermore, since the fraction images are fuzzy datasets they are amenable to fuzzy querying and decision-making, as demonstrated in this paper.

3. The study area

The study area comprises the Kowloon Peninsula of Hong Kong (Fig. 1), which is approximately $160\,km^2$ in extent, and one of the most densely urbanised areas in the world. The most densely built areas are devoid of vegetation, and elsewhere street planting is severely restricted by lack of space (Jim, 2004). The urban area is surrounded by mountainous regions supporting evergreen secondary forests and the urban boundary is usually abrupt, at the foot of steep slopes. Within Kowloon, the main vegetation comprises street trees, local (mainly treed) parks, institutional managed grassland and a few steep inselbergs supporting remnant secondary forest. The avifauna of Hong Kong is considered to be species rich (Lock, 2000), with a total of 450 species recorded in its $1098\,km^2$ land area. Lock (2000) recorded 20% of these in the 14 ha. Kowloon Park which is approximately 6 km distant from the nearest countryside across land. Although she found the avifauna of urban parks in Hong Kong to be more similar to cultivated land than to forest, the Great tit (*Parus major*) which is predominantly a forest bird in Hong Kong, was observed in five out of six urban parks.

4. Methods

4.1. Vegetation mapping

Separate images representing grass and tree pixel fractions were derived by LSU from a December 2001 Ikonos image of 4 m spatial resolution with 4 bands (RGB/IR) (Nichol and Wong, 2007) covering the whole of urban Kowloon. The procedures involve the derivation of pure spectral signatures from each of the main land cover types, known as endmembers. These were obtained by selecting pure, unmixed pixels from the image. Lastly the fractional cover types within each pixel were obtained by the spectral unmixing procedure which is based on the solution of a set of least square equations for n endmembers and n bands. For our study, four endmembers, namely grass, trees, high albedo and low albedo surfaces were selected, and the four Ikonos bands plus an additional NDVI band were used. The end product used in the present study is an image whose pixel values represent the percentage (fraction) of trees within the pixel. Tree cover maps for the study area were also obtained using a standard MLC (whole pixel) classification of the 4 m Ikonos and 20 m SPOT images. This uses training area statistics to allocate each whole pixel to one land cover type. There was no attempt to differentiate between trees and shrubs as distinct life forms in this study since field measurement with a multispectral radiometer showed no significant difference between the spectral reflectance of trees and shrubs. However this may not be a great disadvantage for habitat evaluation since Lock (2000) found that there was significant overlap in the species composition of birds found in urban tree and shrub habitats in Hong Kong, compared with distinctly different species in grassland.

Since the LSU technique assumes that the contribution of the different cover types to the total pixel reflectance is linearly related to their area, some error may be generated, whereby the fractional proportions of the endmembers may not equal 1. Accuracy assessment for LSU is difficult because pixel unmixing does not produce hard boundaries of land cover types whose position and size can be measured. Furthermore, overlay onto a reference dataset of known accuracy is limited by the accuracy of the geometric correction process which is usually only ± 0.5 pixel. In this study this problem was mitigated by using the control points obtained from orthorectification of the 1 m Ikonos panchromatic band, for rectifying the 4 m resolution multispectral image. Thus accuracy assessment, by overlay of 70 Ikonos LSU test pixels onto a high (0.8 m) resolution colour orthophoto minimized errors of co-registration. A maximum error of $\pm 0.3\,m$ over the $16\,m^2$ area of an Ikonos pixel was obtained, which corresponds to $\pm 2.5\,m^2$, or 15%. The position of the Ikonos test pixels on the orthophoto was further verified visually with reference to well-defined features such as plot corners, buildings and intersections. Within each $4\,m \times 4\,m$ Ikonos pixel on the orthophoto the grass and trees were visually interpreted, and their areas screen digitized and measured.

4.2. Least cost path (LCP) analysis

In order to evaluate whether such a high resolution database is necessary for common urban ecological applications, LCP Analysis was undertaken to compare pathways generated from both fine and moderate resolution images, and from both hard and soft classification techniques. The pathways represent routes taken by birds with differing habitat requirements to reach Kowloon Park. The LCP balances habitat suitability, degree of connectivity between starting and end points, and minimum Euclidean distance by considering

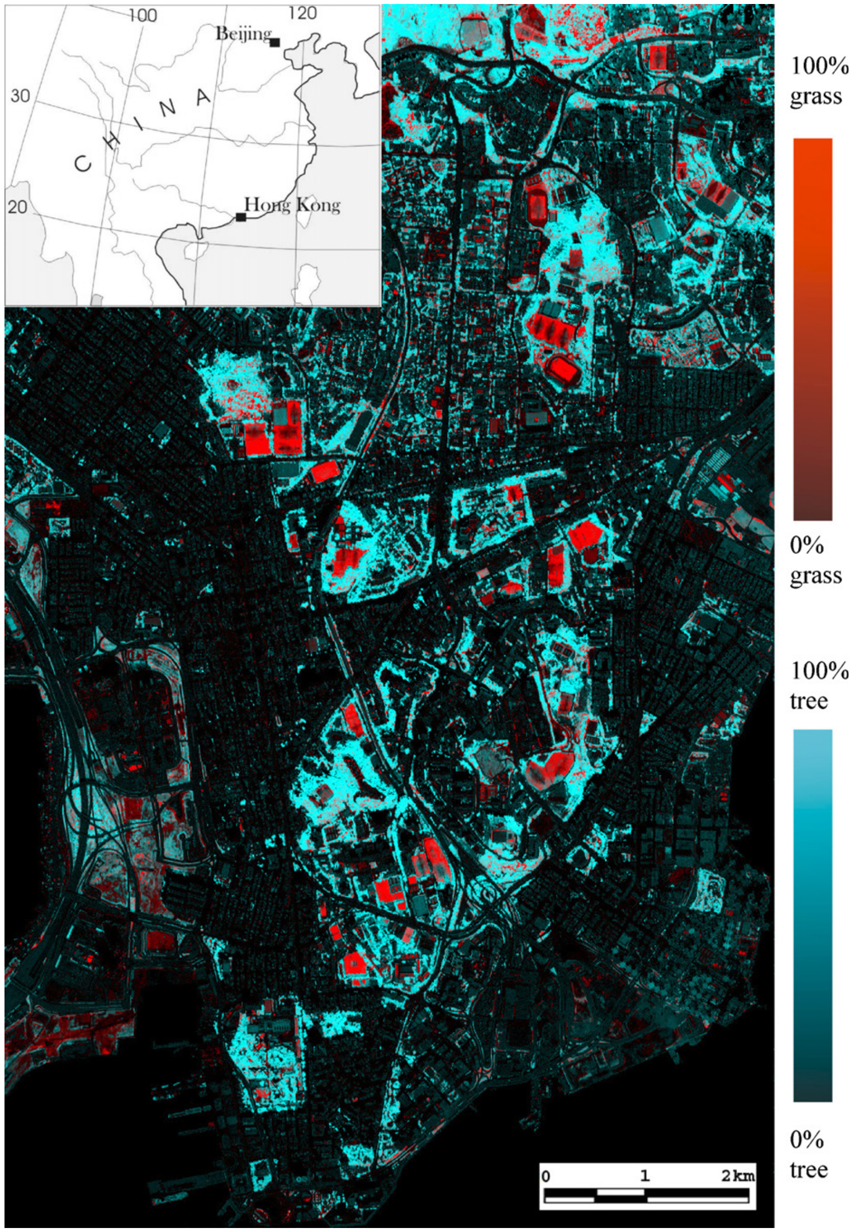

Fig. 1. Grass and tree fraction image derived from LSU, showing grass as red and tree as turquoise. The percentage of grass and/or trees in each pixel is represented by the respective colour brightness, and pixels containing both grass and trees appear magenta.

the cumulative pixel values at each grid point. These considerations are based on previous research which indicates that both local and landscape level factors influence bird abundance and species richness (Blair, 1996; Melles et al., 2003), and that birds will travel much farther across wooded habitats than across small gaps (Desrochers and Hannon, 1997). Thus LCP analysis identifies the path of least resistance across a cost surface, where costs are usually based on the allocation of weightings to whole pixels representing land cover types. This study adopts an innovative approach with the LSU soft classifier, by treating the LSU fractions as a fuzzy dataset whereby weightings are allocated according to the percentage of a single land cover type (in this case tree cover) within a 16 m × 16 m pixel.

Tree fraction images were generated by LSU from 4 m Ikonos multispectral images and imported to IDRISI v.14.02 (Clark Labs, Worcester, MA, USA). The pixel fraction amounts were divided into 5 equal classes for query purposes, and each class was given a weight representing the perceived degree of difficulty for birds to travel across the varying fractions of tree cover (Table 1). This friction surface was then input to the IDRISI COST module which computes a cost surface by considering both the friction value and distance from a defined target. Three different weighting schemes were devised to test for sensitivity to differing fractions of tree cover within a pixel (Table 1). Based on an ending point at the largest urban park, Kowloon Park, and starting at the nearest continuous area of dense forest, the PATHWAY module (Eastman, 2006) was used to compute three LCPs for the three weighting schemes. For comparison purposes, two additional friction surfaces and LCPs were created from less detailed tree cover maps derived from the maximum likelihood (whole pixel) classifier of (i) the 4 m Ikonos image and (ii) a 20 m resolution SPOT image.

Table 1
Left hand part of the table gives the friction values allocated to different tree fraction classes, for input to least cost path mapping. The bird data in the right of the table are derived from four field visits to each route, and numbers in brackets represent computation without habitat generalists (feral pigeon (*Columbus livia*), tree sparrow (*Passer montanus*) and black kite (*Milvus lineatus*)).

Fraction of tree cover	Allocated friction value	Description of route suitability	Density: birds/ha.	Number of species	Insect ivore[a] density	Shannon diversity index	Equita bility index
Route A. Route length: 7454 m (N-S), 3562 m (E-W)							
0.8–1	5		North-South path				
0.6–0.8	50		9.4 (6.6)	15 (12)	1.4	2.26	0.79
0.4–0.6	50	Recognises only dense trees. Lower tree fractions equal to no trees					
0.2–0.4	50		East-West path				
0–0.2	50		8.1 (3.7)	8 (5)	0	1.29	0.62
Route B. Route length: 7358 m (N-S), 3416 m (E-W)							
0.8–1	5		North-South path				
0.6–0.8	10		9.1 (6.7)	14 (11)	0.85	2.27	0.80
0.4–0.6	20	Prefers denser trees but can traverse non-tree as last resort					
0.2–0.4	50		East-West path				
0–0.2	100		12.5 (8)	11 (8)	3.6	1.81	0.75
Route C. Route length: 6473 m (N-S), 3209 (E-W)							
0.8–1	10		North-South path				
0.6–0.8	10		16.8 (9)	19 (16)	1.5	2.37	0.80
0.4–0.6	10	All tree fractions equally suitable; avoids gaps					
0.2–0.4	10		East-West path				
0–0.2	100		21 (11)	12 (9)	1.4	1.89	0.76

[a] Includes common tailorbird (*Orthotomos storius*), great tit (*Parus major*), and yellow-browed warbler (*Phylloscopus inornatus*).

For the purpose of the study, birds are assumed to choose the least cost (optimum) path, since they would encounter fewer hazards, would spend less time in traveling, and would travel through habitat with higher probability of containing food and cover. It is hypothesized that if the allocation of weightings to tree fractions of less than 100% of a pixel were to result in significantly different and shorter routes than for the MLC-based routes, then tree patches smaller than the 16 m^2 of an Ikonos pixel must be important for providing habitat connectivity across the urban landscape. Furthermore, if the biological relevance of the different routes was shown to differ, with birds showing a preference for shorter routes having more fragmented tree cover, this would support the need for such high resolution mapping in urban areas. This hypothesis is supported by previous work indicating that species richness is more related to connectivity and than to habitat area (Jokimaki, 1999; Molainen and Hanski, 2006).

The routes generated by the three weighting schemes for the LSU tree fraction image traverse Kowloon in a generally north-south direction, and are as follows:

(i) In Route A, high friction values were given to all pixels except those with the highest tree fraction value of 0.8–1 (column 2, Table 1), to simulate a route favoured by birds which require a thick tree cover and cannot tolerate sparse, or no trees. This is the longest LSU route, at 7454 m as it is unable to utilise fragmented tree cover, and follows dense tree patches approaching the size of one 4 m × 4 m pixel or larger. It traverses between large patches across the shortest urban distance, not recognising any smaller intervening tree fractions.

(ii) For Route B, the friction weights allocated to the tree fractions were set to increase gradually as the percentage (fraction) of tree cover decreased. This route considers birds which prefer dense tree cover but which could also tolerate lesser amounts, albeit as a lower preference. Route B follows the shortest route C in the southern half but, having more stringent requirements for tree cover, takes a more circuitous path in the northern half, where it is less able to exploit the fragmented tree cover of the residential areas. It thus diverges to follow parks and larger tree patches.

(iii) Route C, where the friction values of all pixels containing any tree fraction are set equal, but lower than those with no tree, represents a requirement for any amount of tree cover along the route but the patch size is not a limiting factor. This is the shortest and most direct route, at 5918 m, as the requirement is for any tree cover regardless of the fraction amount. This route comprises both low density residential development with fragmented tree cover, as well as vegetated linear corridors along the Kowloon-Canton Rail (KCR) line, and a double row of old trees along Wylie Road.

In order to repeat the procedures and verify the robustness of the findings, three additional routes with the same weightings (A, B and C), but in an east-west direction, were generated.

4.3. Field data collection

In order to investigate whether the different LCPs represent real differences in their functionality as bird habitats, fieldwork was undertaken in January and February 2006. Since Kowloon is fully developed, very little vegetation change is known to have taken place in the 4+ years since image acquisition. A slow walk was undertaken along the differing sections of the routes mapped by LSU, recording with binoculars the number and species of birds seen within a 20 m strip on either side of the route. This distance was chosen because DeGraaf et al. (1991) noted that more than 70% of urban birds can be seen within a distance of 20 m, but this falls to 40% at 30 m and only 20% at 40 m. The walks were repeated on 4 separate occasions, and the results averaged. Bird density and species numbers were computed both with and without three abundant species which appear not to require green areas: namely feral pigeon (*Columbus livia*), tree sparrow (*Passer montanus*) and black kite (*Milvus lineatus*), which will be referred to as habitat generalists. The density of insectivores was also noted, since insectivores indicate the development of a more complex food chain, and are deemed to be environmentally sensitive species. They comprise a larger proportion of the birds in rural areas (Beissinger and Osborne, 1982; DeGraaf and Wentworth, 1991) and insufficient, or planted, as opposed to native vegetation may be unable to support them. The insectivores observed in the study include common tailorbird (*Orthotomos sutorius*), great tit (*P. major*) and yellow-browed warbler (*Phylloscopus inornatus*).

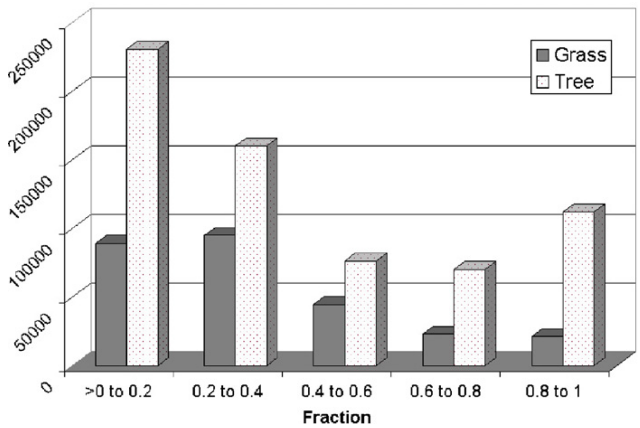

Fig. 2. Histograms showing frequency of pixels containing each of five fraction classes of grass and trees. For example most pixels containing tree cover are in the lowest class, which has only 0–20% of tree cover (i.e. less than 3.2 m^2), indicating extreme fragmentation of tree habitats.

5. Results

5.1. Spectral unmixing

Grass and tree fraction images resulting from LSU are shown in Fig. 1 as a colour composite, with grass displayed as red and trees as blue. Darker hues represent lesser fractions and magenta hues would represent pixels having both grass and trees in varying proportions, although this is uncommon in Hong Kong. High accuracy was demonstrated by the observed adjusted correlation coefficients (R^2) of 0.94 for grass and 0.96 for tree fractions, when compared with a high (0.3 m) resolution digital orthophoto (Nichol and Wong, 2007). The pixel values of the images resulting from LSU represent percentages of grass and/or tree accordingly, within each pixel. The extreme fragmentation of both grass and tree ecosystems in the study area is demonstrated by querying of the pixel values (Fig. 2), which showed that for 84% of pixels containing grass, and 72% of pixels containing trees, the grass and tree fractions occupied less than 60% of the pixel (smaller than 10 m^2), respectively. This indicates the difficulty of mapping urban vegetation over a whole city by field survey or manual air photo interpretation, as well as the likelihood of large error from hard (whole pixel) classifiers such as MLC. The adjusted correlation coefficient for MLC in the same study was 0.77.

5.2. Least cost path analysis from LSU

The three LCPs (routes A, B and C in Fig. 3) were significantly different over most of the routes, for both the north-south (N-S) and the east-west (E-W) routes. Because the N-S and E-W routes were very similar in terms of relationships between tree density and bird populations, discussion will be limited to the N-S routes unless stated, but results for both are given in Table 1.

Field data collected along the three routes indicated, somewhat surprisingly, that route C, the shortest, most direct route not requiring large tree patches, had a 27% higher density of birds, and 32% more species than the other two routes. The higher density and species diversity apply both with and without the three habitat generalists not requiring green areas, and which were present in large numbers. The Shannon Diversity Index, which accounts for both abundance and evenness of species present, was also somewhat higher for route C. Shannon's Equitability Index, whose values lie between 0 and 1, with 1 representing evenness typical of natural habitats, was not significantly different among the three routes (Table 1). Insectivore density was also not significantly different.

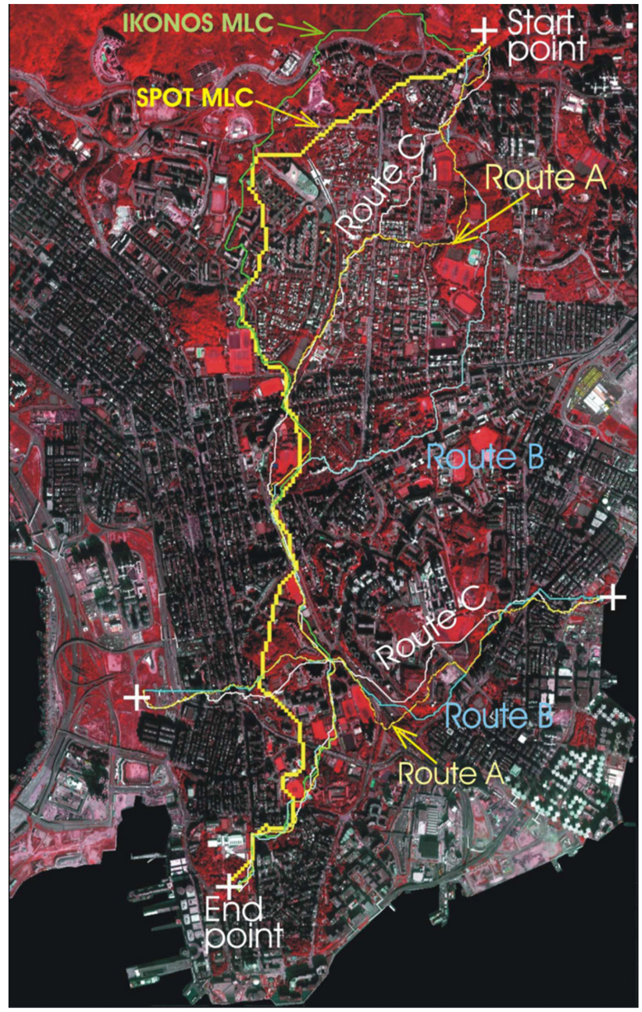

Fig. 3. False colour Ikonos image of Kowloon showing the five north-south routes, and 3 east-west routes derived from the IDRISI PATH module. Route C in both cases is the shortest LSU route.

Visual field observations indicated two possible reasons for the greater richness of birds along route C (the shortest route, with small but more abundant tree patches). Firstly the parks included in the longer routes A and B were often on steep and shady slopes where planting of non-native species has taken place. These include *Acacia confusa*, *Albizia lebbeck*, and *Casuarina equisetifolia* which provide no fruit for birds and produce ecologically impoverished habitats due to tough and un-nutritious leaf litter. Secondly small tree patches as along route C, or even single isolated trees of old native species may be very rich in bird numbers as well as species. For example on several occasion old, isolated rubber trees (*Ficus elastica*) contained more than 30 birds including Red-whiskered bulbuls (*Pycnonotus jocosus*), Chinese bulbuls (*Pycnonotus synensis*) and Asian tree sparrows (*P. montanus*). Along all routes, most birds were observed in trees and appeared to be either foraging, nesting or singing, with little evidence of the routes being used as flyways. Fieldwork for the E-W route was done in summer, as opposed to winter for the N-S route, and while bird density was higher, fewer species were recorded due to the absence of winter visitors such as the Hoopoe (*Upupa epops*), Yellow-browed warbler (*P. inornatus*), and White wagtail (*Motacilla alba*). However, the ratio between routes A, B and C, in terms of bird density, and species number and diversity was remarkably similar, ie. for both N-S and E-W routes, A and B had approximately half of the bird numbers, and substantially fewer species than route C (Table 1).

5.3. Least cost path analysis from whole pixel classifier (MLC)

The two routes derived from the MLC (whole pixel) classifier for Ikonos at 4 m resolution and SPOT at 20 m resolution respectively both appear less able to traverse the urban area than the three Ikonos LSU routes, since they diverge westwards along the forest margin before turning south in the direction of the end point. Although the Ikonos MLC route is identical to the LSU routes in the lower half, the SPOT route differs along its whole length from all others. Since only whole SPOT pixels classified as trees by MLC can be given lower friction values, the route must follow large tree patches of at least 20 m × 20 m. Some of these route differences are also probably due to the mixed pixel problem of whole pixel classifiers, since for SPOT, accuracy for the tree class was only 53%. The only section common to all five N-S paths is a 700 m section along the KCR railway line, which passes through a commercial district devoid of trees. This may be identified as a key connecting corridor linking habitats in the northern and southern sections of the study area.

6. Discussion

The generation of significantly different LCPs from different LSU fraction weightings indicates that tree patches smaller than the 4 m resolution of Ikonos play an important role in the connectivity of tree habitats in the study area. The observation that the shortest, most fragmented route contained both the highest bird numbers and greatest species diversity (excluding habitat generalists) may suggest that such small tree patches may play an important role in supporting birds either individually as habitat islands or due to their enhanced importance as habitat connectors. This finding that small tree patches may be at least as important as larger patches conflicts with the majority of previous studies which show a decline in species diversity with decreasing patch size. However, the patches measured in these studies have usually resulted from the fragmentation of a once continuous natural habitat (Fahrig, 2003) rather than from the planting and landscaping common in urban areas. Moreover, most of these (e.g. Park and Lee, 2000; Donnelly and Marzlufff, 2004; Marzluff, 2005) have investigated landscape parameters at grain sizes an order of magnitude higher than in our study, over larger study areas and over much less densely urbanized landscapes than that of Hong Kong. For example Donnelly and Marzlufff (2004) using Landsat with 30 m resolution identified the threshold size for conserving forest bird species diversity as 42 ha, which is three times larger than the largest urban park in the present study. Bino et al. (2008) also using Landsat suggested that the size of green area needed to maintain bird species diversity was 15 ha. On the other hand, results from more detailed mapping using manual air photointerpretation in a highly urbanized and fragmented landscape in the Paris suburbs (Huste and Boulinier, 2007) indicate that for urban-adapted birds the patch size near the city centre did not control bird diversity, since extinctions were balanced by immigration from nearby patches, and Fahrig (2003) describes many instances where small patches in a landscape have been beneficial to biodiversity. Arthropods which are less capable than birds of traversing urban surfaces may also favour proximity and contiguity over habitat size, and well-connected tree patches in highly urbanized landscapes may promote this, along with well-developed predator–prey relationships, although the incidence of insectivores along the different routes was inconclusive in the present study. Indeed Bolger et al. (2000) found that the abundance of some arthropods was enhanced by fragmentation.

The observation that the routes generated from the whole pixel MLC classifier, and from route A with the largest tree patches, were less able to traverse the urban area, supports the assertions of others (eg. Benson and Mackenzie, 1995; Moody and Woodcock, 1995; O'Neill et al., 1996; Hay et al., 2001) that landscape parameters are dependent on grain size. Indeed, O'Neill et al. demonstrate that a 10% change in land cover class due to change of resolution may result in an 80% change in habitat dominance within sample plots, and they recommend sampling grain sizes 2–5 times smaller than the spatial features of interest. In the present case, the coarser grain sizes of 20 m × 20 m (SPOT) and 4 m × 4 m (Ikonos) from the MLC classifier were unable to identify a direct path across the urban landscape due to the apparent lack of habitat linkages at those resolutions, compared with tree patches of ca. 20% of an Ikonos pixel (ca. 3.2 m^2) detected by LSU.

7. Conclusion

In densely urbanized Hong Kong, tree patches of 400 m^2 and 16 m^2 corresponding to the sizes of SPOT and Ikonos pixels, respectively, do not appear to provide viable connecting corridors for urban birds. Thus in our densely urbanized study area, where green space is extremely fragmented (Fig. 2) sub-pixel analysis of fine resolution images offers a more complete and relevant habitat inventory, and such detailed mapping at whole city level has not been undertaken previously. The fuzzy querying from the LSU soft classifier produced different paths of least resistance for birds across the urban landscape, which were based on differing sizes of micro-scale habitats. The results suggest that in a highly urbanised region, connectivity is of great importance to most species. The method demonstrated here offers a means for testing the importance of connectivity versus patch size, over a whole city, for grass and tree habitats either individually or combined, and permits the designation of relevant wildlife corridors. Moreover, the soft classification approach described, facilitates upscaling to coarser grain sizes for enquiries at differing levels of landscape analysis (Blair, 1996; Hay et al., 2001), by varying the fraction amounts within a pixel, and/or by pixel resampling.

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