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NOTE AND COMMENT

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How to measure the urban-wildland ecotone: redefining 'peri-urban' areas

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Abstract The array of definitions regarding 'peri-urban' areas do not allow the precise measurement of its boundaries in a city. In this study, I developed an easy-to-use method to calculate the area where urban and adjacent non-urban systems intermingle. To validate that such areas were ecologically meaningful, I compared bird community species-richness, abundance, and composition from 'intra-' and 'peri-urban' areas in a medium-sized neotropical city. Results show that 'peri-urban' areas represent an important ecological interaction area for birds, and differ greatly from 'intra-urban' areas. The proposed method is robust and useful for a great variety of amoeboid-growing cities.

Keywords Bird communities · Urban ecology · Urban-wildland ecotone · Intra-urban · Peri-urban · Urban fringe · Neotropics

Introduction

The urban-wildland ecotone is the geographical area that separates 'intra-urban' areas from agricultural, wildland, rural, and even suburban environments surrounding an urban area. Several definitions have been adjudged to 'peri-urban' areas. For example, Williams et al. (2001) define 'peri-urban' areas as: 'low-density housing and road development on the periphery of urban areas, still retaining small areas of rural land within networks of suburban buildings'. Iaquinta and Drescher (2000) define different types of 'peri-urban' areas depending on their origin: (1) 'village peri-urban': areas far from the city that derive from sojourning, circulation, and migration; (2) 'diffuse peri-urban': areas located in the urban fringe that derive from multiple-source points in migration; (3) 'chain peri-urban': areas located in the urban fringe that derive primarily from chain migration; (4) 'in-place peri-urban': areas close to the city that derive from in-place urbanization, natural increase, and some migration; and (5) 'absorbed peri-urban': areas within the city that derive from succession/displacement and traditionalism. In contrast, others simply define 'peri-urban' areas as the 'urban fringe' (Boischio et al. 2006), also referred to as 'urban periphery' (Friedberg 2001) or 'urban edge' (Tjallingii 2000). Finally, some urban ecology studies have defined 'peri-urban' areas as the 'rural adjacent area to a town' (Clergeau et al. 2001; Snep et al. 2006).

Based on the lack of standardized methods to delimit the boundaries of 'peri-urban' areas in the urban ecology literature, I propose an easy-to-use method to measure the urban-wildland ecotone of a city. Because this measurement is based on the geographic interaction between urban areas and adjacent wildlands, it could represent a realistic and measurable way to define and establish 'peri-urban' areas in amoeboid-growing cities with circular/ellipsoid polygons. To validate that such areas were ecologically meaningful, I compared avian species-richness, abundance, and composition in 'peri-urban' and 'intra-urban' sites of a medium-sized neotropical city (Morelia, Michoacán). Because urban areas can represent a geographical barrier for wildlife species (Jokimäki 1999; Fernández-Juricic and Jokimäki 2001), I expected lower bird species-richness within the 'intra-urban' area, represented mainly by a subset of those species recorded in the 'peri-urban' area.

Methods

Study area

Bird surveys were conducted in the city of Morelia (19°42′07″N, 101°11′48″W), the largest city within the

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Cuitzeo watershed and state capital. The city of Morelia has undergone rapid and unplanned development since it was founded, growing 400% in just three decades (1960–1990; López et al. 2001). At present, Morelia covers an area of over 100 km^2 and has a human population larger than 1 million inhabitants (Vargas Uribe 2008).

Delimitation of the 'peri-urban' area and validation

Based on the lack of standardized methods to delimit the 'peri-urban' area of a city, I developed a method to measure the area of interaction between an urban area and adjacent systems. Due to some of its procedures, this method is exclusively useful for amoeboid-growing cities with circular/ellipsoid polygons. To measure the 'peri-urban' area of a city with such geographic traits, its polygon (or metropolitan area) needs to be drawn using an up-to-date satellite image or map. Based on the city's polygon, a 'smoothened city polygon' is required to establish the interaction baseline between the urban core and adjacent systems. This new polygon should be generated, focusing in urban peripheral areas where cities grow amoeboid-likely, by connecting the apex (crest) of each urbanization growth projection with the two most proximate growth projections using straight lines. To measure the area of interaction between urban and adjacent non-urban systems, it is necessary to record the farthest perpendicular distance among urbanization growth projections, between the 'smoothened city polygon' and the city's polygon. Subsequently, the length of the area where urban and adjacent systems intermingle can be determined, with an $\alpha = 0.05$, by calculating the 95% confidence intervals for all the measured perpendicular distances among urbanization growth projections. Finally, to depict the urban-wildland ecotone ('peri-urban' area) of a city on a map, subtract the upper bound 95% confidence interval (=average + 95% CI) from each vertex of the smoothened city polygon, and join them with straight lines to generate a new concentrically smaller polygon. The area between the 'smoothened city polygon' and the new polygon will represent the 'peri-urban' area of the city (Fig. 1).

To assure that this method did not depend on the particular geographic traits of the city of Morelia, I measured the 'peri-urban' area of 15 amoeboid-growing cities from around the world. Of them, three are located in Mexico (Guadalajara, Morelia, Zamora), two in the US (Phoenix, Manti), and one in Brazil (Luziana), Spain (Zaragoza), France (Vitré), Italy (Parma), England (York), Nigeria (Abuja), Yemen (Sana'a), Russia (Pskov), China (Shouxian), and Australia (Mount Isa) (Table 1). Afterwards, I performed a linear regression analysis between the size of these cities and the length of their calculated 'peri-urban' area to assess if this method was scale-dependent.

Bird surveys and analyses

I carried out bird surveys in June 2007 and February 2008 from 07:00 to 10:00 using unlimited radius point counts (following Ralph et al. 1993). Points were located at a minimum distance of 250 m between each other to assure survey independence (Ralph et al. 1993; Huff et al. 2000). Fifteen points counts were carried out within Morelia's 'peri-urban' area and 15 within its 'intra-urban' area, which were visited twice, in summer and winter (Fig. 2).

To evaluate if bird community diversity values differed between the 'peri-urban' and 'intra-urban' area of the city of Morelia, I compared their species-richness values, abundance, and performed a species-turnover analysis. To contrast species-richness values, I compared their rarefaction curves, computed using EstimateS (Sobs [Mao Tao] ± 95% confidence intervals; Colwell 2005). These curves represent the statistical expectation of species accumulation curves based on the repeated re-sampling of all pooled samples (Gotelli and Colwell 2001).

To assess the species-turnover rate between 'peri-urban' and 'intra-urban' areas, I used a recently proposed species-turnover index (β_{sim}; Lennon et al. 2001). β_{sim} quantifies the relative magnitude of species gain and losses in relation to the sample with less unique species, rather than the proportion of shared species in relation to the total sample of species (Koleff et al. 2003; Gaston et al. 2007). Therefore, β_{sim} allows to evaluate if the species composition of the sample with less unique species has changed or just loss species in relation to the sample with more unique species. Both species-richness and species-turnover values were calculated using samples from both surveyed seasons (summer and winter).

Results

Delimitation of the 'peri-urban' area and validation of the method

The procedure for establishing the length (width) of the 'peri-urban' area of cities suited correctly for the 15 studied urban areas. In fact, the linear regression analysis performed between the length of 'peri-urban' areas and the size of each city showed to be strong and significant ($r^2 = 0.97$, $p < 0.001$), demonstrating that this method can be used for a great diversity of amoeboid-growing cities with circular/ellipsoid polygons ranging from 4 to 2140 km^2, at least.

Bird surveys

Bird species-richness was significantly higher in the 'peri-urban' area of the city of Morelia (33 ± 5.5 species) when compared to 'intra-urban' areas (17 ± 3.4 species; Fig. 3, Table 2). This difference did not show to be

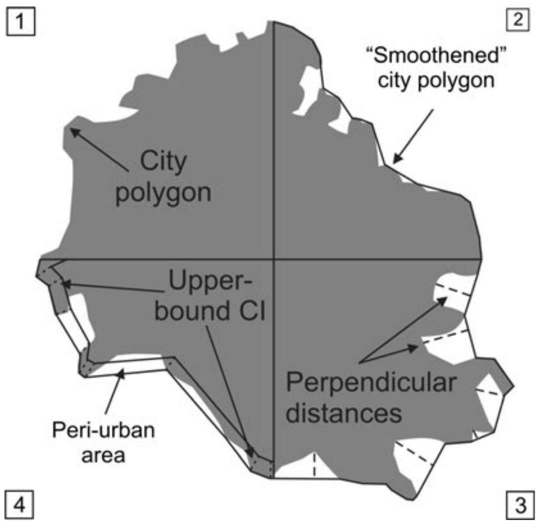

Fig. 1 Example of the procedure to measure the 'peri-urban' area of a city. Step 1: delimit the polygon of the urban area. Step 2: generate a 'smoothened city polygon' by connecting the apex (crest) of each urbanization growth projection with the two most proximate growth projections using *straight lines*. Step 3: record the farthest perpendicular distance among urbanization growth projections between the 'smoothened city polygon' and the city's polygon. Step 4: (a) Calculate the 95% confidence intervals for all the measured perpendicular distances. (b) Subtract the upper bound 95% confidence interval from each vertex of the smoothened city polygon and join them with *straight lines* to generate a concentrically smaller polygon. The area between the 'smoothened city polygon' and the new concentrically smaller polygon will represent the 'peri-urban' area of the city

Table 1 Size and 'peri-urban' length (width) of the 15 studied cities

City	City size (km^2)	Peri-urban area (km^2)
Manti (US)	4.12	0.13
Zhou Xian (China)	6.21	0.30
Vitré (France)	6.29	0.23
Zamora (Mexico)	12.58	0.24
Mount Isa (Australia)	13.64	0.31
Parma (Italy)	25.75	0.35
York (England)	35.65	0.29
Zaragoza (Spain)	41.74	0.41
Pskov (Russia)	45.94	0.40
Luziania (Brazil)	46.01	0.46
Abuja (Nigeria)	80.71	0.56
Morelia (Mexico)	106.4	0.52
Sana'a (Yemen)	117.4	0.63
Guadalajara (Mexico)	448.07	1.16
Phoenix (US)	2,140.78	2.96

density-dependent, as bird abundances were almost identical in both areas ('peri-urban' = 431 individuals; urban = 437 individuals). Of the total recorded bird species, 17 were shared by both studied areas, 17 were exclusive to the 'peri-urban' area, and only 3 were exclusive to the 'intra-urban' area (β_{sim} = 0.15).

Table 2 List of bird species recorded in 'peri-urban' and 'intra-urban' areas of the city of Morelia

	'Intra-urban'	'Peri-urban'
Falconiformes		
Accipitridae		
Accipiter striatus		•
Falconidae		
Falco sparverius		•
Columbiformes		
Columbidae		
Columba livia	•	•
Columbina inca	•	•
Cuculiformes		
Cuculidae		
Crotophaga sulcirostris	•	•
Apodiformes		
Apodidae		
Cynanthus latirostris	•	•
Amazilia beryllina		•
Amazilia violiceps		•
Piciformes		
Picidae		
Melanerpes aurifrons		•
Passeriformes		
Tyrannidae		
Contopus pertinax		•
Pyrocephalus rubinus	•	•
Tyrannus vociferans	•	•
Hirundinidae		
Stelgidopteryx serripennis		•
Hirundo rustica	•	•
Troglodytidae		
Catherpes mexicanus	•	•
Thryomanes bewickii	•	•
Troglodytes aedon		•
Sylviidae		
Polioptila caerulea	•	•
Turdidae		
Turdus rufopalliatus		•
Catharus aurantiirostris		•
Catharus guttatus		•
Mimidae		
Melanotis caerulescens		•
Parulidae		
Vermivora ruficapilla	•	
Dendroica coronata	•	•
Dendroica townsendi		•
Geothlypis speciosa		•
Wilsonia pusilla		•
Emberizidae		
Sporophila torqueola	•	•
Pipilo fuscus	•	•
Cardinalidae		
Piranga ludoviciana		•
Passerina caerulea		•
Icteridae		
Sturnella magna	•	
Quiscalus mexicanus	•	
Molothrus aeneus	•	•
Fringillidae		
Carpodacus mexicanus	•	•
Spinus psaltria	•	•
Passeridae		
Passer domesticus	•	•

Taxonomic order and scientific names follow the AOU's (1998) check-list and further supplements (up to Chesser et al. 2009)

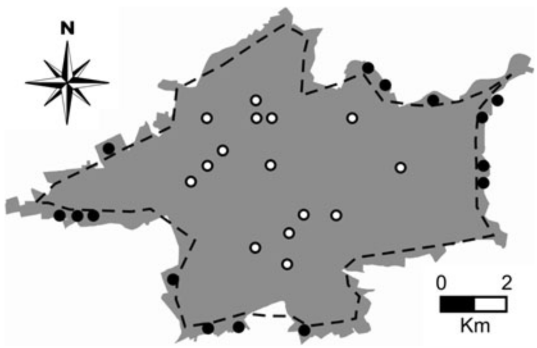

Fig. 2 Location of bird survey points in the city of Morelia. Of the total 30 point counts carried out in summer and winter, 15 were located within the 'intra-urban' area (*hollow circles*) of Morelia and 15 were located among the delimited 'peri-urban' area (*solid circles*) using the proposed method in this paper. The *gray area* represents the polygon of the city of Morelia and the segmented line symbolizes the measured 'peri-urban' boundary

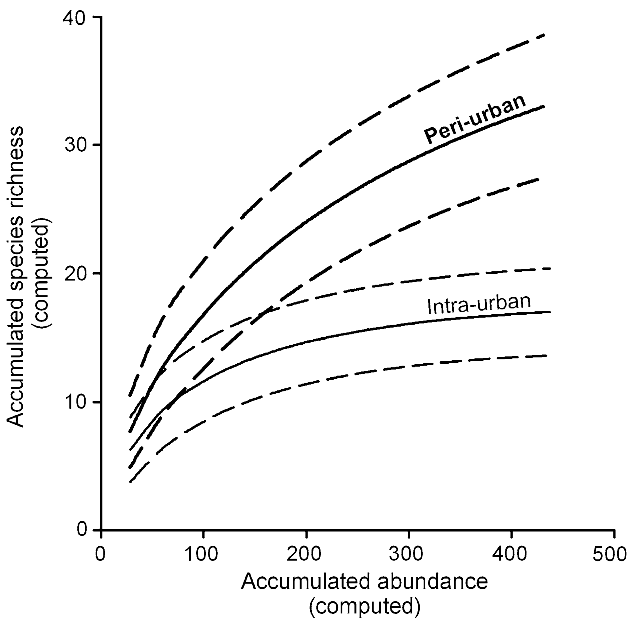

Fig. 3 Rarefaction curves for bird communities recorded in 'peri-urban' and 'intra-urban' areas of the city of Morelia. Although bird abundances were almost identical in both areas, bird species-richness showed to be significantly higher in the 'peri-urban' area. *Solid lines* represent the mean value for the accumulated number of observed species, while *segmented lines* correspond to their 95% confidence intervals

Discussion

The study of biotic transition zones is essential for understanding processes that drive specific biodiversity patterns (Grau et al. 2008). The method proposed in this paper to measure the 'peri-urban' area of cities showed to be robust and useful for a great variety of amoeboid-growing urban areas. Thus, this method comprises a powerful tool to delimit the 'peri-urban' area of cities where urban ecology studies are developed.

Results from this study show that the urban-wildland ecotone ('peri-urban' area) of a city can represent an isolation barrier for bird communities. Although bird community results could be awarded to habitat attribute differences, the studied 'peri-urban' sites include highly developed areas. Recording significantly richer bird communities in the 'peri-urban' area of Morelia and a low species-turnover rate between 'peri-urban' and 'intra-urban' sites suggest the existence of an 'urban semi-permeability' process for birds. Thus, further studies should take into account the bias of comparing sampling sites from 'peri-urban' and 'intra-urban' areas within a city, although they share similar site-specific traits. This phenomenon could also apply to other wildlife groups that are affected by urbanization, such as insects and mammals (Dickman and Doncaster 1987; Juliao et al. 2005; Sinclair et al. 2005). However, these hypotheses remain to be tested.

Based on the ecological barrier effect that 'peri-urban' areas can represent for wildlife communities, at least for birds, I suggest the use of four terms related to the geographical location of urban sites. First, the 'peri-urban' area of a city encompasses the region where the urban core ('intra-urban' area) intermingles with adjacent systems, which boundary can be delimited following the method proposed in this paper. Second, the 'intra-urban' area of a city, also known as inner-urban, inner-city, and/or urban core, comprises the greater portion of a city, located inside the boundaries of its 'peri-urban' area. Third, the 'urban fringe' represents the border of an urban area, where cities sprawl, delimiting the polygon of a city. Fourth, 'extra-urban' areas comprise systems located within the direct area of influence of a city (e.g., micro-watershed), including agricultural systems, suburban/rural areas, and even natural habitats. Even though these four concepts are quite precise, they are not static, and their boundaries should be reconsidered as cities grow.

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