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Anuran species in urban landscapes: Relationships with biophysical, built environment and socio-economic factors.

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Abstract

Urbanisation is a significant threatening process for amphibians, causing loss of habitat, altered hydrology and increased mortality. Impacts operate at different spatial scales and consequences vary depending on the sensitivity of individual species. Most studies of the impact of urbanisation on anurans have occurred in large metropolitan cities. There is a paucity of research in smaller urban settlements where the impacts of development may be less pronounced. We examined the richness and occurrence of anuran species in wetlands in regional towns in south-eastern Australia as a factor of natural and built features occurring at multiple spatial scales, and the socio-economic characteristics of surrounding neighbourhoods. Anuran species richness declined with increasing isolation of wetlands and reduced cover of terrestrial vegetation. The occurrence of two wide-spread anuran species was negatively related to level of urban intensity and positively related to neighbourhood vegetation cover, whereas the converse was true for a third common species. Vegetation cover was greater in neighbourhoods with 'higher' socioeconomic status (e.g. more disposable income). These less developed neighbourhoods occurred on the fringes of towns, often in elevated locations, and tended to support more anuran species. The level of urban intensity increased closer to town centres and more developed neighbourhoods with lower socio-economic status were often built in low-lying areas where wetlands tend to form naturally. Yet, these neighbourhoods harboured few anuran species. Our study suggests that careful planning of low-lying neighbourhoods near town centres and peri-urban neighbourhoods on town fringes is required to ensure anuran conservation in urban settlements.

Key words: amphibians, urbanisation, connectivity, south-eastern Australia, urban wetlands, socio-economics

1. Introduction

Urbanisation is a key threatening process for amphibians (Hamer and McDonnell, 2008), which have shown significant declines globally (Blaustein and Keiseker, 2002; Wilcox, 2006; McCallum, 2007). Urbanisation can adversely affect anuran communities by increasing vehicle-related mortality and habitat isolation (Lehtinen et al., 1999; Elzanowski et al., 2009), and by modifying aquatic and terrestrial habitats, reducing water quality (e.g. via polluted run-off) and changing water flows and infiltration. These factors operate at different spatial scales and their importance varies depending on the sensitivity of individual species and the characteristics of the urban environment (Mazerolle et al., 2005; Price et al., 2005; Gagne and Fahrig, 2007).

At broad scales, road and dwelling density is strongly associated with the level of modification to urban wetlands and can influence the movement of amphibians between suitable habitat (Hamer and McDonnell, 2008), and alter and increase stormwater runoff, negatively impacting tadpole growth and survival (Parris, 2006; Eigenbrod et al., 2008; Hartel et al., 2009). When roads intersect wetlands, they cause loss and fragmentation of habitat and can separate natal ponds from important terrestrial and over-winter locations (Rubbo and Kiesecker, 2005; Pillsbury and Miller, 2008). High density road networks are substantial barriers to amphibian movement and habitat re-colonization, and increase the likelihood of mortality (Knutson, 1999; Ficetola and De Bernardi, 2004; Drinnan, 2005; Price et al., 2005).

At smaller scales (e.g. individual ponds), habitat occupancy can be influenced by a range of factors including the complexity and cover of fringing and aquatic vegetation, presence of fish, hydrology, pond size, and water depth (Parris, 2006; Hamer and McDonnell, 2008; Pillsbury and Miller, 2008). Many anurans shelter in fringing vegetation during the day, which is important for protection from predators, regulating microclimates and providing shelter for males during calling. The structure and type of aquatic vegetation can determine the availability of anchor points for egg masses, provide protection for tadpoles and contribute to tadpole diet and development (Babbitt and Tanner, 2000; Snodgrass et al., 2000; Paton and Crouch, 2002). Permanent water bodies are less attractive to some species than ephemeral ponds, as they are more likely to contain predatory fish (Egan and Paton, 2004; Pearl et al., 2005; Baldwin et al., 2006). Increasing water permanence may also indirectly impact on amphibians by reducing the complexity and cover of aquatic vegetation (Casanova and Brock, 2000).

Most research on the impacts of urbanisation on fauna have occurred in or near major metropolitan centres (population size typically > 1 000 000) and this is largely true for anuran studies (Parris, 2006; Gagne and Farig, 2007; Eigenbrod et al., 2008; Simon et al., 2009). Relatively few studies have been conducted in smaller urban settlements (population size < 100 000) where the impacts of urbanisation may be less pronounced. Moreover, few researchers have examined inter-relationships among fauna species occurrence, abiotic and biotic factors, and the socio-economic characteristics of urban landscapes (although see, for example, Kinzig et al., 2005; Loss et al., 2009). Variation in the richness or abundance of fauna species is often related to the natural features of urban environments (e.g. vegetation cover), but these features may co-vary with the built environment (e.g. housing density), householder behaviour and socio-economic factors such as income, education and home ownership (Hope et al., 2003; Grove et al., 2006; Jenerette et al., 2007; Luck et al., 2009). To fully understand the consequences of increasing urbanisation for anuran conservation, and develop more effective management strategies in urban landscapes, we need to examine the inter-relationships among species occurrence, the natural and built environment, and neighbourhood socio-economic factors.

In this study, we examined the occurrence of anuran species in wetlands located in regional towns in south-eastern Australia as a factor of natural and built features occurring at multiple spatial scales, and the socio-economic characteristics of surrounding neighbourhoods. Our results serve as a valuable comparison to amphibian studies conducted in major cities and demonstrate the importance of understanding the relationships between urban environments and the socio-economic profile of residents.

2. Methods

2.1 Study area

Our study was conducted in nine regional centres [towns] across Victoria and New South Wales in south-eastern Australia (population sizes ranged from 16 845 to 78 221 in 2006; Fig. 1). In each town potential wetland sites were identified via air photo maps and field inspection prior to surveying. From this pool we selected 30 sites in neighbourhoods that represented a range of housing densities and demographics. Wetlands were located on public land and included lakes, constructed wetlands, ox bow lagoons, ephemeral wetlands, storm water ponds, dams and small, low flowing creeks. We did not include concrete water storages, swimming pools, concrete stormwater drains, small ponds with non-natural edges or sites that were highly unlikely to support anurans. We surveyed the 30 sites for anuran species on four occasions throughout the year between December 2007 and October 2008. Species investigated in this study do not have multi-year larval stages and survey times were chosen to coincide with the peak calling activity of species known to occur in the regions and to maximise detectability (Cogger, 2000; Anstis, 2002; Weir et al., 2005).

The definition of ‘urban’ can be context specific (Hahs and McDonnell, 2006; Pickett and Cadenasso, 2006) and has been variously applied in anuran studies (Hamer and McDonnell, 2008; McDonnell and Hahs, 2008). We focused on a range of neighbourhood types to capture as much variation as possible in settlement design. These neighbourhoods could be classified as peri-urban to suburban. Each was within 10 km of a town centre, predominant land use was residential and housing density ranged from < 1 to > 6 houses/ha.

2.2 Anuran surveys

Species occurrence in wetlands was determined by recording anuran calls over two nights on each survey occasion from dusk until midnight. Surveying was done simultaneously at sites located in the same town and recording at each town was rotated over six weeks. An automatic recorder (Faunatech^{TM}) was placed at the waters edge and set to record for a combined length of 32 minutes (eight sessions of 4 minutes each). As time of sunset varied, the interval between each 4 minute recording was altered so that a 50 minute interval was used during earlier sunset times and a 30 minute interval was used for later sunset times. We converted analogue tapes to digital files and identified calls by comparing them to reference libraries (Frogs Australia Network, 2006; Amphibian Research Centre, 2007).

2.3 Selection of explanatory variables

Variables related to the urban environment and likely to influence anuran occupancy patterns were assessed at three different spatial scales (Table 1):

i) 'site scale' – defined as the characteristics of the surveyed water body or its immediate surrounds (e.g. fringing vegetation);
ii) 'local scale – defined as within 500 m of the survey point ; and
iii) 'landscape scale' – defined as within 1000 m of the survey point and including the socio-economic characteristics of the surrounding neighbourhood.

2.3.1 Site scale

Wetland characteristics were measured once at the start of the study, or in the case of ephemeral wetlands during the period of maximum inundation. We visually estimated the following characteristics: (1) the proportion of wetland edge that was fringed with vegetation, including native and non-native herbaceous vegetation that was not mown grass; (2) the proportion of native and non-native woody and herbaceous vegetation within a 5 m band from the waters edge; and (3) the proportion of the waterbody containing aquatic vegetation (Table 1). Hydrology was grouped into two categories - 'permanent' (always wet during the study period) or 'ephemeral' (dry at some point during the study). Information on hydrology was confirmed by local government personnel in each town. The area of the water body was measured onsite or by reference to the geographic information system (GIS) layer 'Vicmap Hydro' (DSE, 2008) for large water bodies (> 6000 m^2). For creek lines, we measured the width of the creek (at the survey point) and collected the same data for all vegetation types for 25 m along either side of the creek (12.5 m up and down stream from the survey point).

2.3.2 Local scale

As information on dispersal distances for Australian frog species is limited, the buffer distances for the local (500 m) and landscape (1000 m) scales were guided by other studies on urban anurans (e.g. Semlitsch and Bodie, 2003; Mazerolle et al., 2005; Price et al., 2005; Parris, 2006). We used ArcMap 9.2 to calculate the proportional cover of roads, vegetation and water in the 500 m distance band. The cover of roads was calculated using the GIS layer 'Vicmap Transport' by selecting all roads within buffers and assigning a width to each road segment based on road class, type and geometry standards (Austroads, 2002; DSE, 2006a). We summed the road segment length by the widths to give a total road cover which was divided by buffer area to give a proportional cover of roads. The proportion of woody vegetation cover ≥ 2 m in height was calculated using the GIS layer 'Vicmap Vegetation' (DSE, 2006b). The proportion of water was calculated using the 'water area polygon' in Vicmap Hydro, which includes permanent and intermittent natural and constructed wetlands (DSE, 2008).

2.3.3 Landscape scale

Proportional cover of roads, vegetation and water was calculated as above for a 1000 m buffer around each survey site (Table 1). The 'isolation' of each surveyed wetland was classified as the distance to the next nearest natural habitable water body (see selection methods for survey sites). Analyses at the landscape scale included the natural, built and socio-economic characteristics of neighbourhoods surrounding water bodies. Neighbourhoods were defined by census collection district boundaries, the smallest area used by the Australian Bureau of Statistics (ABS) to collect detailed demographic data.

To represent the natural environment of neighbourhoods, we collected field data on vegetation characteristics from December 2007 to February 2008 at four randomly located quadrats (20 m × 100 m, and nested quadrats of 20 m × 50 m) in parks or built-up areas within 1000 m of anuran survey sites. In the 20 m × 100 m quadrats, we collected data on the number of native and exotic trees > 20 cm in diameter at breast height. In the nested 20 m × 50 m quadrats, we collected data on the proportion of quadrat area covered in lawn (m^2), understorey vegetation (< 2 m in height), midstorey vegetation (2–4 m), and overstorey vegetation (> 4 m). The abundance of native plants from the families Myrtaceae and Proteaceae was also calculated, as this gave an indication of the ‘nativeness’ of neighbourhood vegetation (> 90% of native plant species in our study areas are from these families).

The built environment of neighbourhoods was represented by dwelling density (dwellings / ha) (ABS, 2006) and the proportional cover of impervious surfaces other than roads (measured in the 20 m x 50 m quadrats described above). We also collected data on the socio-economic variables household disposable income, education level, and the proportion of home owners in each neighbourhood (ABS, 2006), which have been shown to relate to the natural and built environment of neighbourhoods (Hope et al., 2003; Grove et al., 2006; see Table 1 and Luck et al., 2009 for further details).

2.4 Statistical analysis

Our dependent variables were observed species richness and individual species occurrence (presence/absence). We modelled these against the explanatory variables both within each spatial scale and across scales to determine the most parsimonious model in each instance. We then examined the relationships between the environmental variables that best predicted probability of occurrence and the socio-economic characteristics of neighbourhoods. Data were checked for normality and equality of variance and transformed where necessary using arcsine (square root), log or square root transformations (Zar, 1999). We considered using relative species richness (species detected/local species pool) rather than observed species richness as some detected species did not occur across the entire range of the study (see Cam et al., 2000). However, these two measures were highly correlated ($r = 0.962$, $p < 0.001$) so we retained the latter.

To avoid including highly correlated ($r > 0.6$) explanatory variables in the same model, we omitted some variables or created composite variables using principle component analysis (SPSS 16.0.0, Tabachnick and Fidell, 2007). Non-native and native vegetation cover in the 5 m band were highly correlated, so we combined the categories and considered all woody vegetation and herbaceous vegetation. An urban intensity index was derived from neighbourhood dwelling density, and the proportion of impervious surface and road cover in the 1000 m buffer using principle component analysis. The first principle component (PC1) explained 54% of variation in the data. A neighbourhood vegetation index (NVI) was derived from all vegetation transect variables measured in the neighbourhood with PC1 explaining 49.4% of variation in the data.

The urban intensity index was highly positively correlated with various measures of urbanisation and the NVI was highly positively correlated with measures of vegetation cover (see Table S1 in supporting information). We modelled both composite variables and the original variables used to create them (not including highly correlated variables in the same model) to determine if the more simple urban or vegetation measures were better predictors of species richness or occurrence.

2.4.1 Species richness

To reduce the number of explanatory variables, we first identified those variables that were significantly correlated with species richness and/or led to a significant reduction in model deviance through single variable analysis using a hierarchical generalized linear model with a Poisson probability distribution and log link function. We then modelled species richness with this subset of variables using the same approach. To avoid overfitting models due to a small sample size, our modelling was restricted to combinations of ≤ 3 independent variables (Harrell et al., 1996). We used a hierarchical model to reflect the spatial structure of the data whereby survey sites were nested within towns. Hence, 'town' was included as a random factor in each model, and other explanatory variables were included as covariates. Modelling was conducted using the software program LISREL 8.8 (Jöreskog and Sörbom, 2001).

Models were ranked using an Information Theoretic Approach and Akaike's Information Criterion (AIC) based on the second order derivative, AIC_c, which is appropriate when the sample size divided by the number of parameters in the model containing the most parameters is < 40 (Burnham and Anderson, 2002). We compared the difference in the criterion values of the best ranked model to model i (Δ_i). Models where Δ_i is < 2 are usually considered to have substantial empirical support; values between 2 and 4 suggest some support, while values > 4 indicate little support (Burnham and Anderson, 2002). Akaike weights (w_i) were also calculated and these can be interpreted as the probability that any given model is the best model in the suite of models being considered. We also calculated the summed Akaike weight for each explanatory variable (i.e. summing w_i across the models that the variable occurred in) as a measure of the relative importance of each variable, and model-averaged estimates of effects (model-averaged coefficients; Burnham and Anderson, 2002). Model fit was assessed by comparing the AICc value of the more complex models with the constant only model and the model including only the constant and random effect ('town').

2.4.2 Species occurrence

We modelled the occurrence of three species that had sufficient sample sizes (minimum number of 'present' sites = 8) and occurred across the entire survey region using logistic regression. These were *Limnodynastes dumerilii* (Banjo frog), *Limnodynastes tasmaniensis* (Spotted marsh frog) and *Litoria ewingii.*gp. As distinguishing *Litoria ewingii* (Southern brown tree frog) and *Litoria paraewingi* (Victorian frog) calls from recordings alone is difficult, these two species were grouped together to form *L. ewingii.*gp. We chose not to model *Crinia signifera* (Common froglet) as it was only absent in 6 sites (see Table S3 in supporting information).

We used a two-step process to reduce the number of explanatory variables and generate a subset for further modelling. First, two-tailed T-tests were used to compare the values of the continuous biophysical variables at sites where a species was present or absent. Variables were excluded if they did not differ substantially between sites ($p > 0.2$; Hosmer and Lemeshow, 2000). Simple logistic regression models were then used to test the relationship between each of the remaining variables in turn (including categorical variables) and the presence/absence of each of the three species (see Table S4 in supporting information). The fit of these models was assessed using Pearson's chi square and the Hosmer-Lemeshow statistic. We then modelled individual species with this subset of variables using a hierarchical logistic regression model (as described above). As the sample size in the smallest category of the binary models did not allow modelling of more than one parameter (Harrell et al., 1996), we modelled probability of occurrence against a single variable only in the hierarchical models. These models were then ranked using AIC as described above.

In some cases, accounting for detection probability is important to avoid bias when making inferences about individual species presence or absence (Wintle, 2004; Mazerolle et al., 2005; MacKenzie et al., 2006), but we chose not to include detection parameters in our models. Based on survey effort and the individual species modelled, we are confident that if species were present at a site we would have detected them on at least one occasion. All three species have a wide calling window, are abundant in our study area, and are most active in calling during the seasons we surveyed (Anstis, 2002).

2.4.3 Socioeconomic and habitat relationships

To determine if there were any relationships between wetland and terrestrial habitat variables and the demographics of surrounding neighbourhoods, we created a composite variable 'socio-economic status' using principle component analysis and the variables disposable income, education level and home ownership. The first principle component explained 63% of variation in the data and component scores were highly positively correlated with all three of the original variables ($r > 0.6$) (Table S1). We included socio-economic status in the preliminary main effects analysis of species richness and individual species occurrence to explore direct effects (Table S4). However, we expect socio-economic status to influence anuran species richness and occurrence indirectly through its relationships with urbanisation and habitat measures (e.g. urban intensity and vegetation cover). Therefore, we investigated whether socio-economic status of neighbourhoods was related to the most important predictors of amphibian richness and occurrence (i.e. urban intensity, NVI and habitat isolation).

3. Results

3.1 Species richness

Eleven species were recorded during the survey period, including two species listed under the *Threatened Species Conservation Act 1995* NSW and the *Flora and Fauna Guarantee Act 1988* Vic. At least one species was present at 27 of the 30 sites with a maximum of seven species recorded at one site. The most common species were *C. signifera* (24 sites) and *L. ewingii.*gp (14 sites). Five other species occurred in at least 8 sites (Table S3). Ten variables were significantly related to species richness (see Table S2 in supporting information); most occurred at the landscape scale. Only one variable each was associated with richness at the site and local scales; herbaceous vegetation and the proportion of vegetation cover within 500 m, respectively.

Anuran species richness was positively associated with measures of vegetation (NVI, vegetation cover at 1000m and 500m, and native indicator) and negatively associated with increasing habitat isolation, herbaceous vegetation cover (within 5 m of the water's edge) and measures of the built environment (urban intensity, impervious surfaces and dwelling density). We selected isolation, urban intensity, NVI and vegetation cover at 1000 m for further modelling based on change in deviance from the single variable analysis (Table S2). Wetland type also appeared to explain variation in species richness but this was mainly due to the fact that creeks had a much lower incidence of frog species than all other wetland types. Therefore, we chose not to model this categorical variable. Moreover, the values of each continuous variable did not differ between wetland types.

The highest ranked model explaining variation in species richness included only habitat isolation, and this was a substantial improvement over the constant + random effects model (Table 2). However, given the data, there was only moderate support for this being the best model among the candidate set ($w_\mathrm{i} = 0.32$) and eight other models had a $\Delta_i < 4$. The relative importance of particular explanatory variables can be gleaned from the summed w_i for each variable. Habitat isolation had the highest summed w_i of 0.62 followed by vegetation cover at 1000 m (0.39). In addition, the 95% CIs of the model-averaged coefficients did not encompass zero for these two explanatory variables (see Table 3).

3.2 Species occurrence

Variables measured at larger scales had the strongest relationships with the occurrence of the three individual anuran species. The best model predicting the occurrence of *L. ewingii* gp. included the composite variable urban intensity, and this was a substantial improvement over the constant + random effects model (Table 2). The model including this variable had good support ($w_\mathrm{i} = 0.96$) and the 95% CIs of the co-efficient of urban intensity did not encompass zero (Table 3). The best model predicting the occurrence of *L. tasmaniensis* included the composite variable NVI ($w_i = 0.68$), however this was one of three models with $\Delta_i < 4$ (Table 2). Nevertheless, NVI was the only variable with 95% CIs that did not encompass zero (Table 3).

The highest ranked model predicting the occurrence of *L. dumerillii* also included NVI ($w_i = 0.73$). The next best model included urban intensity and both models had $\Delta_i < 4$ and were substantial improvements over the constant + random effects model (Table 2). The 95% CIs of NVI did not include zero, while they just included zero for urban intensity (Table 3). In contrast to models for *L. ewingii*.gp and *L. tasmaniensis*, the probability of occurrence of *L. dumerillii* was greater with decreasing neighbourhood vegetation and increasing urban intensity.

3.3 Socio-economic and habitat associations

Of the three variables that best predicted species richness (urban intensity, NVI and habitat isolation,), NVI was the only variable that had a strong, positive association with socio-economic status (Tables 4 and 5). The best model predicting NVI included socio-economic status and was a strong improvement on the constant + random effects model. This was one of three models with $\Delta_i < 4$, but socio-economic status was the only predictor with 95% CIs that did not encompass zero. Urban intensity was more reliably predicted by distance from the central business district (CBD) + socio-economic status. This model was also one of three with $\Delta_i < 4$ but distance from CBD was the only variable with 95% CIs that did not encompass zero. Habitat isolation was not strongly related to any socio-economic or biophysical variable. However, towns differed in the mean isolation of sites; generally towns in the Victorian Riverina Bioregion (see Fig. 1.) had less isolated sites than towns outside this region (see Table S5 in supporting information).

4. Discussion

4.1 Species richness

Anuran species occupied a range of urban wetland types in our study area. Level of wetland isolation was an important predictor of species richness in concordance with a number of studies from larger metropolitan areas (Lehtinen et al., 1999; Ficetola and De Bernardi, 2004; Parris, 2006; Rubbo and Kieseker, 2005; Pillsbury and Miller, 2008). However, urban intensity and road density were less important in predicting species richness in our study area than in the metropolitan studies of Parris (2006) and Pilsbury and Miller (2008). This may reflect variation in urbanisation level, road density as well as reduced traffic impacting on anuran mortality

(Eigenbrod et al., 2008). For example, Parris (2006) recorded a road density of 0–24% in a 500 m buffer around wetlands, whereas in our study it ranged from 3–15%. Pillsbury and Miller (2008) noted a road density of 0.6–26% (1000 m buffer); in our study it was 2–11.5%.

Landscape-scale factors were more influential than site or local scale factors in predicting species richness and the probability of occurrence of the three anuran species. This aligns with previous findings (Mazerrole, 2005, Price et al., 2005; Pillsbury and Miller, 2008; Simon et al., 2009). However, we found that wetland size did not have a significant relationship with species richness, in contrast to Parris (2006) who found that species richness was significantly higher in larger ponds. Large ponds can have greater levels of habitat complexity, but this is not always the case in urban environments. Many of the larger sites in our study had permanent deep water, low habitat complexity and very little aquatic vegetation. Vegetation cover, at the landscape scale, was also an important predictor for species richness and this aligns with other studies which have shown vegetation cover surrounding wetland sites providing important upland habitat for anurans (Drinnan 2005; Hamer and McDonnell 2008; Pillsbury and Miller 2008). Thus efforts to promote vegetation cover in urban areas between wetlands sites could contribute substantially to anuran conservation.

4.2 Species occurrence

The three species we modelled could be regarded as urban tolerant, as they are considered resilient to habitat degradation and are encountered often in anuran surveys in south eastern Australia (Hazell et al., 2004, Parris, 2006, Lane and Burgin, 2008; MacNally et al., 2009). However, the level of tolerance for *L. tasmaniensis* and *L. ewingii.*gp appears restricted as the probability of occurrence for both these species declined within increasing urban intensity. Moreover, we argue that the positive relationship between urban intensity and probability of occurrence of *L. dumerilii* reflects the fact that the most developed urban areas occurred on low-lying flats with sandy soils (preferred by this burrowing frog species), rather than a preference by the species for urbanised locations per se.

Some anurans exhibit a comparably high level of specialisation related to particular site attributes and this can determine species distribution patterns and abundance (Rubbo and

Kieseker, 2005; Hamer and McDonnell, 2008). Sensitivity to habitat modification is also species specific and more degraded sites are likely to be dominated by a few widespread species (McKinney, 2002; Ficetola and De Bernardi, 2004). *C. signifera* appeared to be the most urban tolerant species in our survey, occurring in many different wetland types. This species is regarded as very adaptable, utilizing any habitat within its range (Cogger, 2000; Anstis, 2002). *L. dumerilii* is also able to use a broad range of habitats (Hazel et al., 2003) and appeared to be tolerant to certain levels of urban development (although see above). Surprisingly *L. tasmaniensis* was not encountered as often as *C. signifera* despite being regarded as similarly resilient (MacNally, 2009). *L. ewingii.*gp was also not as common as expected, despite being a tolerant species with a flexible life history strategy and the ability to colonise a range of habitats (Lauck et al., 2005). This suggests than even moderate levels of urban development may negatively impact on these species, and this possibility warrants further investigation.

4.3 Socio-economic factors

Socio-economic status was a strong predictor of neighbourhood vegetation cover, which in turn was positively related to anuran species richness and occurrence (except for *L. dumerilii*) – supporting the contention that terrestrial habitat is important for the persistence of anurans (Drinnan, 2005). Neighbourhoods with 'higher' socio-economic status (more disposable income and a higher proportion of home owners and residents with a tertiary degree) have been shown previously to support greater vegetation cover owing to lower housing density, more elaborate gardens and more greenspace (Martin et al., 2004; Grove et al., 2006; Hope et al., 2006; Luck et al., 2009). In our study area, neighbourhoods with higher socio-economic status tend to occur in elevated locations, whereas lower socio-economic status neighbourhoods occur in low-lying areas where wetlands are more likely to form naturally. This suggests that town-planning strategies that improve vegetation cover in neighbourhoods with lower socio-economic status may yield substantial benefits for anuran conservation.

Distance to the central business district (CBD) was also strongly related to urban intensity, reflecting a gradient in urbanisation level ranging from highly urbanised near town centres to less developed in peri-urban, fringe neighbourhoods. These fringe neighbourhoods tended to support more anuran species and have a larger number of intermittent water bodies. However, they are also the first sites considered for urban expansion as a town population increases (Hammer et al., 2004; Hanson et al., 2005; Radeloff et al., 2005). Therefore, population growth in our study towns and the expansion of town boundaries could cause substantial fragmentation and degradation of existing wetlands that support a large proportion of the urban anuran population. Yet, most of our study towns (five of seven) are built beside major rivers and urban development is currently limited in floodplain areas. These areas, which contain important ephemeral wetlands and ox bow lakes in close proximity to urban neighbourhoods, could support source populations of anurans that may re-colonise urban ponds after local extinction.

Our study suggests that careful planning of both low-lying neighbourhoods near town centres and river floodplains, and peri-urban neighbourhoods on town fringes is required to ensure the conservation of anuran species in urban settlements.

4.4 Conclusion

Habitat suitable for some anuran species is still available in urban areas of regional towns. However, the diversity of aquatic habitats is low and the majority of wetlands are permanent with low complexity of aquatic vegetation and reduced cover of terrestrial vegetation. As a result, the majority of wetlands within urban areas are only suitable for a small group of widespread species that have a broad range of habitat tolerances. Shallow, well vegetated and temporary wetlands are not common in urban landscapes, but are more likely to occur in towns with flood plains, lower development pressure, and in fringe/peri-urban areas. In Australia, peri-urban areas are experiencing increasing pressure for housing development in both metropolitan cites and regional towns (ABS, 2005; DSE, 2007). However, new housing estates usually require storm water retention ponds to mange run off and control erosion (Environment Australia, 2002). With careful planning, these ponds could be constructed to include shallow/ephemeral areas with diverse fringing and aquatic vegetation, and greater habitat complexity. However design needs to address the risk of these areas becoming ecological traps (Hamer and McDonnell, 2008) due to the potential accumulation of pollutants, and further research is required to mitigate these negative effects. If these strategies are adopted particularly in towns which already retain a flood plain zone, there is great potential to improve habitat and maintain amphibian species diversity in urban and suburban areas.

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Table 1. Summary of biophysical, built environment and socio-economic variables collected in this study that have been reported to influence anuran occurrence in urban landscapes (see Luck et al., 2009 for details of socio-economic variable calculations).

Table 2. The highest ranked models ($\Delta i < 4$) examining relationships between wetland, local and landscape-scale characteristics and anuran species richness and individual species occurrence. AIC_c: Akaike's Information Criterion; Δi: The difference in the criterion values of the best ranked model to model *i*; *wi*: Akaike weights; NVI: native vegetation index; WV: woody vegetation; FrV: fringing vegetation

Table 3. The summed Akaike weights (w_i), model-averaged coefficients (β) and their standard error (SE) and upper and lower confidence intervals (CI) for each variable included in the species richness and occurrence models. NVI: native vegetation index; WV: woody vegetation; FrV: fringing vegetation

Table 4. Socioeconomic and geographic models predicting urban intensity, neighbourhood vegetation (NVI) and wetland isolation. AIC_c: Akaike's Information Criterion; Δi: The difference in the criterion values of the best ranked model to model *i*; *wi*: Akaike weights

Table 5. The summed Akaike weights (w_i), model-averaged coefficients (β) and their standard error (SE) and upper and lower confidence intervals (CI) for each variable included in the urban intensity, neighbourhood vegetation (NVI) and wetland isolation models.

Table 1.

Variables	Abbreviation	Description	Data source
Site		*Immediate area of wetland*	
% fringing vegetation not lawn	FrV	Proportion of the wetland perimeter covered in vegetation that was not maintained lawn	Field
% aquatic vegetation	AqV	Proportion of the wetland surface covered in aquatic vegetation	Field
Proportion of woody vegetation (5m band)	WV(5m)	Proportion of the wetland perimeter covered in woody vegetation out to 5m	Field
Proportion of herbaceous vegetation (5m band)	HV(5m)	Proportion of the wetland perimeter covered in woody vegetation out to 5m	Field
Hydrology	Permanent or ephemeral	Permanent = always wet Ephemeral = dry at one time during the survey	Field
Wetland type	Creek or pond	Creek = linear waterway system, low flowing Pond = body of standing water	Field
Wetland size	Small, med, large	Small = <1000m^2 Medium = 1000 – 5000m^2 Large = > 5000m^2	Vicmap hydro
500m buffer		*Area within 500m radius of survey point*	
Proportion of water	Water 500m	Summed areas of all water polygons	Vicmap Hydro
Proportion of roads	Roads 500m	Summed road length plus width adjustment for road class	Vicmap Transport
Proportion of vegetation cover	Vegetation 500m	Summed areas of vegetation polygons (sparse, medium, dense)	Vicmap Vegetation
1000m buffer		*Area within 1000m radius of survey point*	
Distance from CBD	Dist CBD	Distance of survey site to the centre of town	Arcmap
Distance to nearest waterway or pond	Isolation	Distance to the nearest wetland/waterway not on the same system	Arcmap
Proportion of water	Water 1000m	Summed areas of all water polygons	Vicmap Hydro
Proportion of roads	Roads 1000m	Summed road length plus width adjustment for road class	Vicmap Transport
Proportion of vegetation cover	Vegetation 1000m	Summed areas of vegetation polygons (sparse, medium, dense)	Vicmap Vegetation
Neighbourhood		*Census collection district area*	
Dwelling density	Dwelling density	Number of houses divided by the area of the census collection district (houses/ha)	ABS 2006 census

Proportion of impervious surfaces	Impervious surfaces	Proportion of pavement, driveway, footpaths, etc. within 1000m^2 quadrat	Field
Proportion of lawn	Lawn	Proportion of lawn within 1000m^2 quadrat	Field
Proportion of under, mid and overstorey vegetation	Understorey veg Midstorey veg Overstorey veg	Proportion of vegetation in the three structural bands within 1000m^2 quadrat	Field
No. of native flowering plants	Native indicator	Number of plants from the families Myrtaceae and Proteaceae within 1000m^2 quadrat	Field
No. of trees	Trees	Number of trees (>20cm DBH) within 2000m^2 quadrat	Field
No. of native trees	Native trees	Number of native trees (>20cm DBH) within 2000m^2 quadrat	Field
Socio-economic		*Census collection district area*	
Income	Income	Mean weekly disposable income	ABS 2006 census
Education	Education	Proportion of residents with a Bachelor degree or higher	ABS 2006 census
Home ownership	Ownership	Proportion of residents who own their home or have a mortgage	ABS 2006 census

Table 2.

	AICc	Δ*i*	*wi*
Species richness models			
Isolation	-26.3	0.0	0.32
Isolation + vegetation 1000m	-24.0	2.2	0.10
Vegetation 1000m + urban intensity	-23.8	2.4	0.10
NVI	-23.4	2.9	0.08
Urban intensity	-23.3	2.9	0.07
Isolation + vegetation 1000m + urban intensity	-23.2	3.1	0.07
Vegetation 1000m	-22.7	3.6	0.05
Isolation + NVI	-22.5	3.7	0.05
Isolation + urban intensity	-22.4	3.9	0.05
Constant only model	-15.6		
Constant + random effects	-22.0		
L. ewingii.gp			
Urban intensity	34.6	0.0	0.96
NVI	40.9	6.2	0.04
Socioeconomic status	41.2	7.0	0.03
Constant only model	43.2		
Constant + random effects	41.7		
L. tasmaniensis			
NVI	33.1	0.0	0.68
Urban intensity	35.3	2.4	0.21
WV (5m)	36.8	3.7	0.11
Constant only model	41.6		
Constant + random effects	38.3		
L. dumerilii			
NVI	24.1	0.0	0.73
Urban intensity	26.7	2.6	0.20
Socioeconomic status	28.6	5.0	0.06
Vegetation 500m	35.1	11.0	0.01
FrV	36.2	12.0	0.01
Constant only model	41.6		
Constant + random effects	32.7		

Table 3.

	∑*wi*	β	SE	Upper CI	Lower CI
Species richness					
Isolation	0.62	-0.02	0.01	-0.00004	-0.04
Vegetation 1000m	0.39	0.93	0.43	1.76	0.10
Urban intensity	0.36	-0.20	0.11	0.01	-0.41
NVI	0.24	0.09	0.31	0.69	-0.50

	wi	β	SE	Upper CI	Lower CI
L.ewingii.gp					
Urban intensity	0.96	-1.58	0.72	-0.17	-2.99
NVI	0.04	0.67	0.44	1.54	-0.19
Socioeconomic status	0.03	0.63	0.43	1.47	-0.21
L.tasmaniensis					
NVI	0.68	1.20	0.55	2.28	0.13
Urban intensity	0.21	-1.04	0.55	0.02	-2.11
WV (5m)	0.11	-2.11	1.35	0.51	-4.74
L.dumerilii					
NVI	0.73	-1.69	0.73	-0.26	-3.11
Urban intensity	0.21	1.84	0.96	3.72	-0.04
Socioeconomic status	0.06	-1.02	0.53	0.02	-2.10
Vegetation 500m	0.003	4.47	1.88	8.15	0.80
FrV	0.002	-3.53	3.00	2.32	-9.39

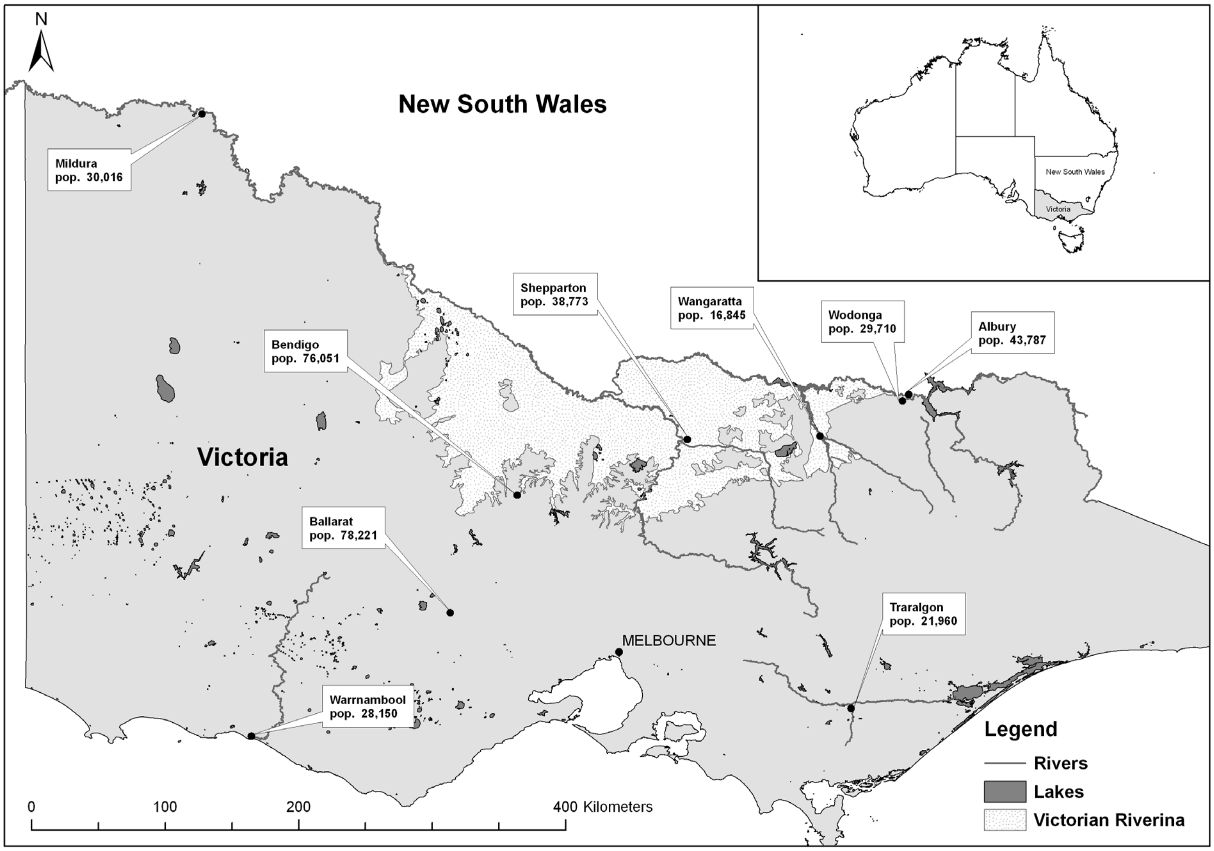
Table 4.

	AICc	Δ_i	w_i
Urban intensity			
Distance to CBD + socioeconomic status	74.8	0.0	0.52
Distance to CBD	75.8	1.0	0.31
Socioeconomic status	77.0	2.2	0.17
Constant only model	86.1		
Constant + random effects	85.3		
NVI			
Socioeconomic status	81.5	0.0	0.45
Distance to CBD	82.1	0.6	0.34
Distance to CBD + socioeconomic status	83.0	1.5	0.21
Constant only model	86.1		
Constant + random effects	85.9		
Isolation			
Socioeconomic status	99.8	0.0	0.51
Distance to CBD	100.6	0.8	0.34
Distance to CBD + socioeconomic status	102.2	2.5	0.15
Constant only model	110.8		
Constant + random effects	98.4		

Table 5.

	$\sum w_i$	β	SE	Upper CI	Lower CI
Urban intensity					
Distance to CBD	0.83	-0.03	0.01	-0.01	-0.05
Socioeconomic status	0.69	-0.43	0.38	0.31	-1.17
NVI					
Socioeconomic status	0.66	0.35	0.10	0.55	0.15
Distance to CBD	0.55	0.01	0.06	0.14	-0.10
Isolation					
Socioeconomic status	0.66	0.14	0.19	0.51	-0.23
Distance to CBD	0.49	0.00	0.01	0.02	-0.02

Figure 1. Location of study areas and population size for each town. Map shows major rivers and lakes near study sites and the Victorian Riverina Bioregion.



Supporting information

Table S1. Pearson correlations between the environmental variables and the native vegetation index (NVI), urban intensity and socioeconomic status. Table also shows principle component (PC1) loadings for the three composite variables. Values in bold indicate the variables used to create the three indices.

Variable	**Correlation**			**PC1 loadings**		
	NVI	Urban intensity	Socioeconomic status	NVI	Urban intensity	Socioeconomic status
Impervious surfaces	-0.805	**0.808**	-0.391		0.808	
Roads 1000m	-0.466	**0.816**	-0.585		0.816	
Roads 500m	-0.370	0.641	-0.350			
Dwelling density	-0.211	**0.539**	-0.229		0.539	
Understorey vegetation	**-0.350**	0.232	-0.191	-0.350		
Vegetation 1000m	-0.056	0.179	-0.042			
Vegetation 500m	0.003	0.163	-0.018			
Midstorey vegetation	**0.194**	-0.257	0.098	0.194		
Lawn	**0.495**	-0.356	0.093	0.495		
Trees	**0.802**	-0.406	0.274	0.802		
Overstorey vegetation	**0.836**	-0.489	0.407	0.836		
Native trees	**0.877**	-0.693	0.414	0.894		
Native indicator	**0.894**	-0.730	0.272	0.877		
Income	0.436	-0.637	**0.929**			0.929
Home ownership	0.332	-0.499	**0.812**			0.812
Education	0.119	-0.166	**0.613**			0.613

Table S2. Variables associated with anuran species richness, where $p \leq 0.20$. Preliminary main effects models show residual deviance and significance (null deviance was -24.14). NVI: neighbourhood vegetation index; HV: herbaceous vegetation.

Variable	**Bivariate Correlations**		**GLM Hierarchical**	
	Pearson's Correlation	*p*(2-tailed)	Deviance	Estimate *p*
Isolation	-0.424	0.020	-30.7	0.03
Urban intensity	-0.430	0.018	-27.8	0.05
NVI	0.266	0.155	-27.8	0.33
Vegetation 1000m	0.468	0.009	-27.1	0.02
HV(5m)	-0.380	0.038	-25.2	0.11
Dwelling density	-0.245	0.192	-30.2	0.18
Impervious surfaces	-0.558	0.001	-27.1	0.005
Native indicator	0.347	0.059	-27.6	0.14
Vegetation 500m	0.412	0.024	-26.4	0.05
Wetland (pond or creek)	Categorical		-34.6	

Table S3. Frog species detected during the survey and the number of sites where they were present. ([a] Vulnerable *Threatened Species Conservation Act 1995* NSW, [b]Threatened *Flora and Fauna Guarantee Act 1988* Vic)

Family/species	**Common name**	**No. of sites**
Myobatrachidae		
Crinia signifera	Common froglet	24
Crinia parasignifera	Plains froglet	10
Crinia sloanei[a]	Sloane's froglet	1
Limnodynastes dumerilii	Eastern banjo frog	11
Limnodynastes fletcheri	Barking marsh frog	1
Limnodynastes peronii	Stripped marsh frog	8
Limnodynastes tasmaniensis	Spotted marsh frog	8
Neobatrachus sudelli	Common spadefoot	1
Pseudophrine bibroni[b]	Bibron's toadlet	1
Hylidae		
Litoria ewingii.gp	Southern brown tree frog/Victorian frog	14
Litoria peroni	Peron's tree frog	9
All species		27

Table S4. Comparison of habitat variables at sites where individual species were absent or present. Preliminary main effects models include the -2 log likelihood, significance values and Nagelkerke r-squared (r^2) for single variable logistic regressions. HV: herbaceous vegetation; WV: woody vegetation; NVI: neighbourhood vegetation index.

Species	**Variable**	**Mean (±SE)**		**T-Test**		**Preliminary main effects**		
		Absent	Present	t	*p* (2-tailed)	-2 Log likelihood	Sig.	r^2
L. ewingii.gp	Urban intensity	0.42 (0.12)	-0.54 (0.34)	-2.65	0.018	32.71	0.03	0.326
	Socioeconomic status	-.24 (0.19)	0.31 (0.33)	1.45	0.163	38.66	0.15	0.103
	NVI	-0.23 (0.19)	0.31 (0.32)	1.43	0.169	38.74	0.15	0.100
L. tasmaniensis	NVI	-0.38 (0.17)	0.60 (0.34)	2.49	0.025	32.54	0.03	0.281
	Urban intensity	0.31 (0.11)	-0.53 (0.42)	-1.90	0.083	34.22	0.05	0.218
	WV(5m)	0.50 (0.08)	0.33 (0.08)	1.43	0.164	37.59	0.19	0.081
L. dumerilii	Vegetation 500m	0.42 (0.07)	0.73 (0.07)	-3.20	0.004	30.86	0.016	0.340
	Urban intensity	-0.32 (0.25)	0.56 (0.12)	3.15	0.004	31.21	0.04	0.328
	NVI	0.29 (0.26)	-0.50 (0.13)	-2.70	0.012	33.97	0.06	0.227
	Socioeconomic status	0.24 (0.22)	-0.41 (0.30)	-1.76	0.094	35.95	0.10	0.150
	FrV	0.63 (0.02)	0.55 (0.05)	1.46	0.166	36.73	0.11	0.117

Table S5. Details of the 30 survey sites. Created wetlands: site created or pre-existing that has been enhanced by revegetation activities, including created storm water mitigation ponds; dam: water body similar to farm dam; intermittent: shallow water body with wet and dry period; pond (small and medium): permanent water body in park setting; creek: permanent running creek; lake: large permanent water body; DD: dwelling density; isolation: distance to the closest waterway; and Bioregions refers to Victorian Bioregions (DPI, 2008).

Town	DD	Type	Size (m^2)	Isolation (m)	Bioregions
Shepparton	2.35	Created wetland	50	712	Victorian Riverina
Wodonga	5.33	Created wetland	736	43	Victorian Riverina
Wodonga	0.90	Created wetland	3,000	462	Victorian Riverina
Wodonga	6.13	Created wetland	3,600	60	Victorian Riverina
Ballarat	4.84	Created wetland	4,000	60	Victorian Volcanic Plain
Ballarat	4.12	Created wetland	4,400	2578	Victorian Volcanic Plain
Albury	0.01	Created wetland	11,311	300	Victorian Riverina
Traralgon	3.73	Created wetland	13,000	912	Gippsland Plain
Wangaratta	6.10	Creek	23	552	Victorian Riverina
Wangaratta	7.63	Creek	35	1276	Victorian Riverina
Warrnambool	5.67	Creek	43	1439	Victorian Volcanic Plain
Traralgon	1.02	Creek	50	91	Gippsland Plain
Traralgon	4.98	Creek	50	2880	Gippsland Plain
Wodonga	1.27	Dam	250	300	Victorian Riverina
Albury	1.12	Dam	707	245	Victorian Riverina
Mildura	0.47	Dam	816	2545	Murray Scroll Belt
Bendigo	3.95	Dam	1,578	448	Goldfields
Albury	6.31	Intermittent	450	1047	Victorian Riverina
Shepparton	4.45	Intermittent	987	90	Victorian Riverina
Warrnambool	1.21	Intermittent	2,000	185	Warrnambool Plain
Shepparton	4.38	Intermittent	2,221	117	Victorian Riverina
Warrnambool	0.51	Intermittent	3,217	1038	Warrnambool Plain
Bendigo	1.74	Lake	23,000	117	Goldfields
Bendigo	3.03	Lake	25,000	817	Goldfields
Ballarat	3.09	Lake	49,094	1214	Victorian Volcanic Plain
Bendigo	4.04	Lake	9,505	212	Goldfields
Warrnambool	2.26	Pond	85	1711	Warrnambool Plain
Bendigo	3.80	Pond	2,000	551	Goldfields
Ballarat	2.19	Pond	4,000	1274	Victorian Volcanic Plain
Albury	3.02	Pond	5,000	925	Victorian Riverina

References

DPI, 2008. Victorian Riverina, Victorian Resources Online. Department of Primary Industries, Melbourne, Victoria. http://www.dpi.vic.gov.au/DPI/Vro/vrosite.nsf/pages/veg_managemt_victorian_riverina