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Srivari Illam, No. 61, Karthik Nagar, 10th Street, Saravanampatti, Coimbatore, Tamil Nadu 641035, India  
Registered Office: 3A2 Varadarajulu Nagar, FCI Road, Ganapathy, Coimbatore, Tamil Nadu 641006, India  
Ph: +91 9385339863 | [www.threatenedtaxa.org](http://www.threatenedtaxa.org)  
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Cover: Long-tailed Shrike *Lanius schach* resting on a dry branch after courtship. Digital illustration on Procreate. © Aakanksha Komanduri.



## Importance of integrating multiple criteria in breeding habitat management for urban frogs and toads (Amphibia: Anura) in Jakarta City, Indonesia

Mohamad Isnin Noer<sup>1</sup> , Ivan Hafidhuddin<sup>2</sup> , Agung Sedayu<sup>3</sup> , Ratna Komala<sup>4</sup>  & Alvira Salsabila<sup>5</sup> 

<sup>1,3,4,5</sup> Program Studi Biologi, Faculty of Maths and Sciences, Universitas Negeri Jakarta, Gd. Hasjim Asjarie It.9. Jl, Rawamangun Muka, Jakarta 13220, Indonesia.

<sup>2</sup> Central Proteina Prima, Jakarta 12920, Indonesia.

<sup>1</sup> mohamadisin@unj.ac.id (corresponding author), <sup>2</sup> hafidhuddinivan@gmail.com, <sup>3</sup> asedayu@unj.ac.id, <sup>4</sup> ratna\_komala08@yahoo.co.id, <sup>5</sup> alvrab@gmail.com

**Abstract:** This study assessed the local and landscape factors that support breeding habitats for native frog species in Jakarta, the capital city of Indonesia. We surveyed 25 wetlands categorized into two management states and varying local and landscape features. Our results revealed that frog species exhibit diverse habitat preferences for breeding; some species prefer constructed or managed environments, some depend on more natural or minimally managed habitats, and one species was highly linked with vegetation cover and light intensity. These findings emphasize the need to incorporate multiple criteria when designing strategies to support breeding habitats for all native frog species in Jakarta. We also explored specific factors influencing breeding site selection, providing insights into the drivers of breeding habitat preferences in urban environments.

**Keywords:** Anthropogenic, conservation, green infrastructure, landscape ecology, native, urban wetland.

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**Author details:** MOHAMAD ISNIN NOER is currently working in the Program Studi Biologi at Universitas Negeri Jakarta, with a research focus on urban and acoustic ecology, especially reptiles and amphibians. IVAN HAFIDHUDDIN is a recent graduate of the BProgram Studi Biologi at Universitas Negeri Jakarta, with an interest in studying reptiles and amphibians. AGUNG SEDAYU is currently pursuing his doctoral degree at Universitas Indonesia, with a research focus on urban plant biodiversity. RATNA KOMALA is a professor in the Program Studi Biologi at Universitas Negeri Jakarta, focusing on marine ecology. ALVIRA SALSABILA is a student in the Program Studi Biologi who actively studies reptiles and amphibians.

**Author contribution:** MIN contributed to conceptualizing ideas and hypotheses, designing methodology, conducting investigations, analyzing data, and writing manuscripts. IH helped in providing field data (investigation), statistical analysis, and data visualization. AS contributed to detailing the research ideas and methods, validating results, and refining the discussion. RK added insight into the manuscript, refining the methodology, and validating the results.

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## INTRODUCTION

Urban environments are experiencing a high degree of land-use changes to support ever-increasing human populations and economies. As a result, natural habitats that support native wildlife species are unsustainably degraded in terms of both quality and quantity (Wang & Kintrea 2021; Pereira et al. 2022). Only a few native species can tolerate these dramatic changes and would likely persist in the remaining remnant patches of habitats (Callaghan et al. 2021; Hahs et al. 2023). Frogs are considered key-stone species living in urban environments (Hutto Jr & Barrett 2021). The ongoing degradation of natural habitats has driven even the most resilient of frogs to cope with degraded habitats left over by humans, known as constructed habitats (Scheffers & Paszkowski 2013). Although utilizing degraded and constructed habitats poses greater risks to the survival of the frogs, finding an isolated or inaccessible natural habitat is more costly considering the risks of bypassing unsuitable urban matrixes (Klop-Toker et al. 2016; Watchorn et al. 2023).

The utilization of urban habitats by frogs is not only to find prey and seek shelter, but they also utilize these areas as breeding habitats to find mates and reproduce (Watchorn et al. 2023). Breeding habitats for frogs are usually unique with certain characteristics that probably might not always be obtained in their foraging habitats (Băncilă et al. 2017; Nakanishi et al. 2020). Male frogs find a mate by vocalizing sporadically to get attention from the females that could be at some distance (Wells 1977). Thus, a greater chance of getting a mate is influenced by the greater efficacy of acoustic signals (Gridi-Papp et al. 2006; Simmons et al. 2013). The trade-off of choosing high-quality habitats persisting in isolation can be compensated for by selecting medium or low-quality habitats but gaining better access for movements and dispersal. The quality of the aquatic habitat used by frogs to deposit eggs is also pivotal to ensure the development and survival of their offspring. However, the presence of ubiquitous disturbances and fragmentation in urban environments is highly reducing the access of urban frog populations to find suitable habitats for breeding. Thus, frogs need to compensate for the risks of finding a suitable breeding habitat by choosing a novel habitat in an urban environment. Instead of considering multiple factors in their breeding decision, they are constrained to settle down for few fundamental criteria in selecting a breeding habitat in the urban environment (McCaffery et al. 2014; Băncilă et al. 2017).

Previous studies have reported that frogs could

utilize constructed or managed habitats (Simon et al. 2009; Holzer 2014; Hutto Jr & Barrett 2021) either foraging or breeding even though the preferences are highly associated with the level of synurbism. Synurbic species are usually well adapted to substantial changes made by humans, thus the potential risks are negligible (Feoktistova et al. 2020). However, some urban areas have retained many nature-dependent or seminatural species that require habitats with low disturbances and changes (Scheffers & Paszkowski 2013). In general, there are so many factors considered by frogs to choose their breeding habitat in urban environments, which generally can be classified into two categories based on their role, specifically local and landscape factors. Local factors are strongly linked to the quality of breeding habitats, encompassing the key parameters that frogs require to ensure breeding success and support the growth and survival of their offspring. Landscape factors relate to the extent of human interference at breeding sites, which influence the environmental conditions preferred by certain frog species. In urban environments, frogs are likely face trade-offs when selecting breeding habitats, as areas that offer both suitable local and landscape conditions are scarce (Pope et al. 2000). As a result, we expect that frogs will select breeding habitats based on the most influential conditions available in urban environments, in an effort to minimize the cost of finding ideal habitats. The selection may likely vary in all species found in the city since each species of frog has a different fundamental niche and sensitivity level.

Jakarta is one of Indonesia's major urban centres that supports a vast and densely packed human population spread across various districts. The urban landscape exhibits marked disparities in the distribution of green spaces. Central regions, typically characterized by extensive urbanization, contain minimal natural areas. In contrast, peripheral zones often feature substantial green spaces, with some areas maintaining access to semi-natural habitats (Ardiansyah et al. 2018; Hwang et al. 2020). A tiny body of research studying frog diversity exists in some parts of the city, reporting a quite diverse frog composition in such suboptimal habitat patches. Approximately, nine species of frogs have been documented in this city, displaying different habitat preferences (Rushayati et al. 2023). Till date, no study has exclusively focused on the breeding activities of Jakarta frogs. Thus, this study attempted to examine the breeding site selection of frogs within these urban environments, focusing on some remaining patches of green areas in Jakarta City.

## MATERIALS AND METHODS

### Sampling Sites

A total of 25 wetlands were surveyed sporadically in 2022 and 2023 encompassing a diverse urban landscape in Jakarta, Indonesia. The study areas covered private areas, parks, fishing sites, and vacant lots. We conducted frog surveys at the beginning of the rainy season when many frogs started breeding activities. These areas were categorized into two distinct groups based on their levels of management intensity, allowing for a comparative analysis of how human intervention influences habitat suitability. In addition, we assessed the factors that contribute to the attractiveness of these habitats for breeding, shedding light on how urban green spaces, despite varying degrees of modification, continue to play a crucial role in supporting wildlife, particularly frogs.

### Breeding survey

Breeding activities and frog abundance were determined using an acoustic approach from 1900–2100 h WIB. Most urban frogs in the city of Jakarta are selective breeders that vocalize exclusively in their breeding sites or period, they would not produce calls outside those constraints. Thus, the acoustic survey is reliable for assessing the breeding habitat of frogs in Jakarta. Some areas, such as private lands, were also difficult to access and explore at night for conducting visual search, utilizing an acoustic survey was best for these circumstances. If available, we also incorporated mating calls for some species of frogs to ascertain that the sites surveyed were utilized by frogs for breeding activities. Frogs were identified acoustically using a database provided by Xeno-Canto (Xeno-canto Foundation, 2026), frog voices of Borneo (Inger et al. 2017), and other information sources from previous studies, such as (Márquez & Eekhout 2006; Kurniati et al. 2010). The number of individual frogs in each site was estimated using the method outlined by Scheffers & Paszkowski (2013). We used an 180°-point count for 10 minutes to detect the vocalization and count the number of males calling within 50 m. Based on our preliminary surveys, 10 minutes of observation is adequate to detect nearly all species in the city of Jakarta. We used 20 minutes pre-observation to ensure there were no undetected or cryptic species that did not emit calls during observation.

### Local and landscape variables

We measured six local and five landscape variables for all surveyed sites. We recorded all local variables directly in the field at the time when frogs were

sampled to ensure that all variables represent the exact condition of their breeding habitat. Six local variables comprised of one management state and five water chemistry parameters. Management state was classified into managed and unmanaged sites following the description proposed by Garcia-Gonzalez & Garcia-Vazquez (2011). We defined ‘unmanaged sites’ as areas that were not subject to any form of management or control. In contrast, ‘managed sites’ were those where vegetation, particularly surface vegetation, is frequently mowed, and leaf litter is regularly cleared. To accurately classify all sites into proper categories, we carried out day surveys (immediately after night surveys) to quantify management state as well as water chemistry parameters. Water chemistry parameters measured in this study were turbidity, temperature, salinity, pH, and total nitrogen using LAQUA NO3 2000-S ION NITRATE/PH/ORP/TEMP. METER. All five water chemistry parameters were measured randomly at three distinct locations within a single site. Five landscape variables recorded were normalized difference vegetation index (NDVI), normalized difference water index (NDWI), normalized difference building index (NDBI), land surface temperature (LST), and light intensity. Landscape variables were mapped within 1 km of the surrounding site by creating a buffer and the data were extracted using zonal statistic plugin. NDVI, NDWI, and NDBI were extracted from Landsat 8 L2SP taken at or near the time when the survey was conducted. LST and light intensity respectively were extracted from Terra/MODIS provided by NASA at 0,1 degrees of resolution and VIIRS night-time lights provided by Earth Observation Group (EOG). All landscape variable analyses were performed using QGIS 3.38.

### Data analysis

The number of calling individuals per site was used to characterize male abundance and were organized into two distinct categories of site management (managed and unmanaged). In order to determine which local and landscape variables are the best predictors for breeding occurrence in 25 surveyed wetlands, we used a generalized linear regression model (GLM) with a binomially distributed error term and a logit link function in R 4.4.1 using lme4 package. We tested five local and four landscape models consisting of nine multivariate models. Models were evaluated using Akaike’s information criterion adjusted for small samples (AICc) to determine the best variables that predict the occurrence of breeding activities. The smallest value of  $\Delta AICc$  was chosen as the top model, while the value of

$\Delta AICc < 2$  was considered as the best predictive model. Since some species of frog were very rare such that their sightings sample size does not entertain running statistical analyses, we ran this model evaluation only on three common frogs with adequate sighting frequencies obtained in our study.

### RESULTS

This study recorded six species of frogs that utilize the remnant green areas of Jakarta as their breeding habitat. The most common or generalist species that occupied urban wetlands for breeding were *Duttaphrynus melanostictus*, *Hylarana nicobariensis*, and *Polypedates leucomystax*. In contrast, others were found in a deficient number of detections (Table 1). *Duttaphrynus melanostictus* was considered more generalist in terms of their utilization of breeding sites, it was found breeding in unmanaged and managed sites. Most other frog species were also found using these two habitats but were more likely to breed in unmanaged habitats (Figure 1). Only one species, *Fejervarya limnocharis*, was found utilizing unmanaged habitat exclusively for breeding.

The occupancy of *H. nicobariensis* was best predicted by NDVI (Normalized Difference Vegetation Index) and

light, which were consistently identified as the most influential landscape predictors. These two factors appeared in three out of the four top models evaluated, highlighting their significance in determining habitat preference. On a more localized scale, pH levels and total nitrogen were identified as the most important predictors influencing *H. nicobariensis* occupancy, as detailed in Table 2. This suggests that while local variables play a role, the species tends to prioritize landscape-level features when selecting breeding sites, as evidenced by models with  $\Delta AICc$  values of less than two, indicating strong model performance. The interplay between landscape and local variables underscores the complexity of habitat selection for this species, with landscape factors exerting a stronger influence.

For *D. melanostictus*, local variables played a more significant role in predicting their occupancies compared to landscape variables, as shown in Table 3. Among these local variables, pH and total nitrogen were identified as the strongest predictors, explaining the selection of breeding sites with a  $\Delta AICc$  of less than two, indicating robust model performance. Interestingly, NDVI (Normalized difference vegetation index), while not the best predictor, also appeared as a landscape-level predictor for *D. melanostictus*, similar to its role in the occupancy models for *H. nicobariensis*. Despite

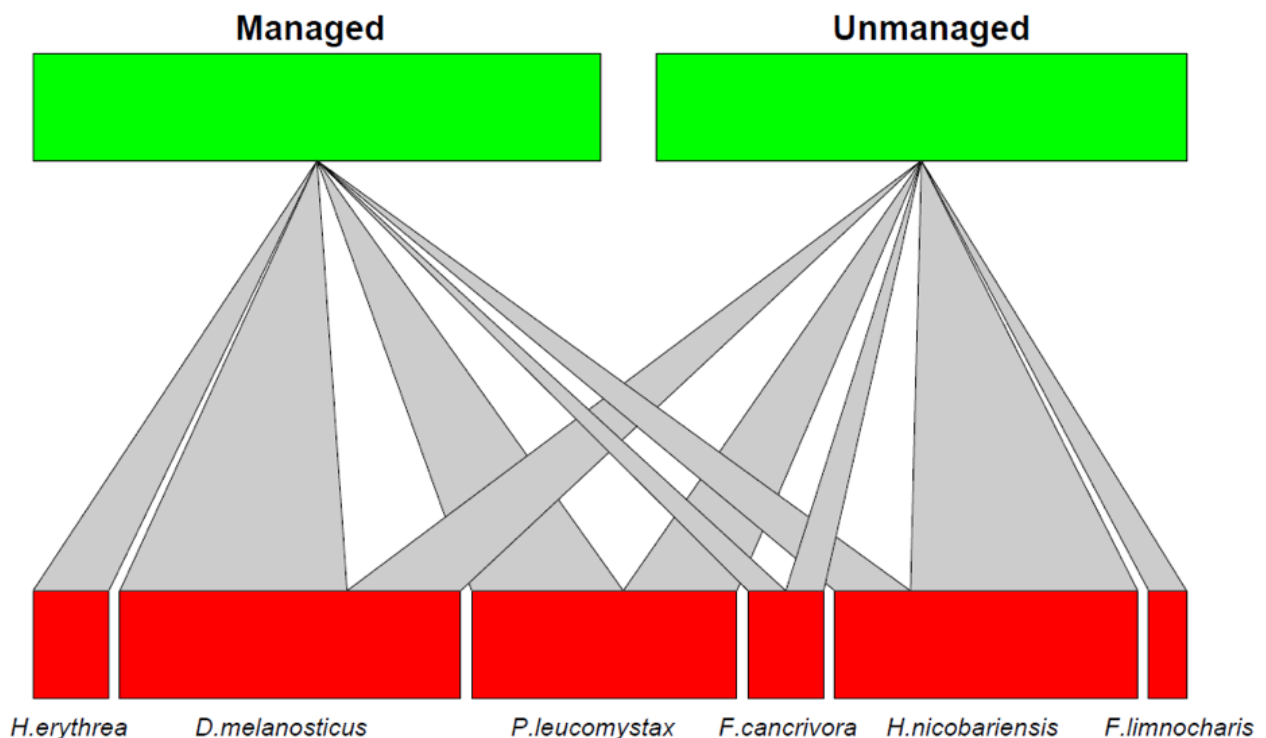


Figure 1. Anuran occupancies in two distinct types of habitats depicting the adaptive selection of some species in selecting breeding sites (managed and unmanaged).

**Table 1. Occupancy and abundance of six anurans organized based on site management types.**

Species	Type	N	Occ <sup>a</sup>	% Occ <sup>b</sup>	Abundance <sup>c</sup>
<i>D. melanostictus</i>	Unmanaged	28	3	14.28	3.11
	Managed	26	6	28.57	2.16
<i>F. cancrivora</i>	Managed	1	1	4.76	0.08
	Unmanaged	1	1	4.76	0.11
<i>F. limnocharis</i>	Unmanaged	3	1	4.76	0.33
	Managed	0	0	0	0
<i>H. erythraea</i>	Managed	6	2	9.52	0.5
	Unmanaged	0	0	0	0
<i>H. nicobariensis</i>	Unmanaged	63	6	28.57	7
	Managed	18	2	9.52	1.5
<i>P. leucomystax</i>	Unmanaged	18	3	14.28	2
	Managed	11	4	19.04	0.91

<sup>a</sup>—Occurrences of anuran species | <sup>b</sup>—Percent occurrences between two management types | <sup>c</sup>—Mean abundance based on two management types.

its presence, NDVI was not considered a top predictor for *D. melanostictus*, emphasizing the species' stronger reliance on local environmental factors over broader landscape features when choosing breeding habitats. This distinction highlights the varying degrees of influence between local and landscape variables on different species' habitat preferences.

As expected for *P. leucomystax*, pH and total nitrogen were the best predictor variables explaining this species' occupancy. However, our models demonstrated that landscape variables were also important variables to consider. Four of five models revealed the inclusion of NDVI, LST, and light as the best-explained predictors for breeding site selection by *P. leucomystax* (Table 3).

## DISCUSSION

Frog surveys in the city of Jakarta have not been conducted intensively, making scientific data on frogs in this city scarce. This study provides important information to fill the gap in the species that inhabit Jakarta's urban ecosystem and breeding site selection, which can be used as baseline information to enhance urban biodiversity in Jakarta. By selecting 25 sites of breeding sites across urban landscapes, we found six species of frogs residing in Jakarta. Most of the frogs are generalist and synurbic species that are capable of utilizing urban habitats and matrices (Iskandar 1998), only one species (*H. erythraea*) which is considered exceptional since this frog is usually

found in rural areas.

Our findings demonstrated that most species were capable of using both managed and unmanaged sites for breeding, as only *F. limnocharis* was obtained exclusively in unmanaged sites. However, species that utilized both types of sites showed different occupancies on those sites. *Duttaphrynus melanostictus* is found more often in managed sites, whereas *H. nicobariensis* is found in unmanaged sites. *Duttaphrynus melanostictus* is a synurbic toad that favours a human-modified environment. This species is capable of using man-made structures for foraging and breeding. In the context of breeding habitat, *D. melanostictus* can utilize areas that contain many human populations and less vegetated areas or natural habitats (Bickford et al. 2010), including stormwater ponds, in the middle of the city. Seemingly, this toad's tadpole fundamentally has developed adaptive features to cope with urban disturbances such as shortening the larval periods (Mahapatra & Mahapatra 2015; Mogali 2017; Saidapur 2025). In line with our findings which found undemanding features of the habitat chosen by *D. melanostictus* to breed. This frog only considers pH and total nitrogen as a fundamental requirement for breeding. *Duttaphrynus melanostictus* would thrive in water bodies with a neutral to slightly alkaline due to the essential pH for optimal egg development and larval survival (Rout et al. 2019). Total nitrogen is another critical factor, as it affects the nutrient availability in breeding sites. Higher nitrogen levels can enhance algal growth, thus providing adequate food for tadpoles to grow more quickly in the changing environment of urban city (Edirisinghe & Amarasinghe 2011).

*Hylarana nicobariensis* is commonly found in disturbed areas (Inger & Stuebing 1997), favouring swampy areas in urban environments (Kurniati & Hamidy 2017). This frog is typically abundant in the city's fringe, but some manage to survive around the city centre. The breeding habitat used by this frog in urban is a bit more complex than *D. melanostictus* or even somewhat in contrast, even though they can occupy the same habitat on some occasions. The dependency of this frog on swampy areas characterized by the lower rate of human frequentation is the reason why this frog has a greater connection with NDVI and other landscape parameters associated with the lower level of human frequentation. The quality of landscape features is probably linked with other landscape-derived features, such as moisture. Previous study highlighted the importance of moist environments for the breeding and survival of *H. nicobariensis*, indicating that inhabiting swampy areas with higher NDVI is beneficial to maintaining acceptable

**Table 2. Occupancy models for nine predictor variables observed for *Hylarana nicobariensis*.**

Variable categories	Predictors	K	AICc	Delta_AICc	AICcWt	Cum.Wt	LL
Landscape	NDVI+Light	3	27.91	0	0.53	0.53	-10.25
	NDVI+LST+Light	4	30.12	2.2	0.17	0.7	-9.81
	LST+Light	3	30.91	3	0.12	0.82	-11.75
	NDVI+NDWI+NDBI+LST	5	32.93	5.01	0.04	0.96	-9.46
Local	pH+TN	3	31.3	3.39	0.1	0.92	-11.95
	Sal+pH+TN	4	34.39	6.48	0.02	0.98	-11.95
	Type+Sal+pH+TN	5	34.86	6.95	0.02	1	-10.43
	Type+Turbid+Sal+pH+TN	6	38.82	10.91	0	1	-10.41
	Type+Turbid+Temp+Sal+pH+TN	7	38.86	10.95	0	1	-8.12

**Table 3. Occupancy models for nine predictor variables observed for *Duttaphrynus melanostictus*.**

Variable categories	Predictors	K	AICc	Delta_AICc	AICcWt	Cum.Wt	LL
Local	pH+TN	3	30.75	0	0.58	0.58	-11.67
	Sal+pH+TN	4	33.04	2.29	0.18	0.76	-11.27
	LST+Light	3	35.03	4.28	0.07	0.91	-13.81
	Type+Sal+pH+TN	5	36.49	5.74	0.03	0.95	-11.25
	Type+Turbid+Temp+Sal+pH+TN	7	41.39	10.64	0	1	-9.39
Landscape	NDVI+Light	3	34.63	3.88	0.08	0.85	-13.61
	NDVI+LST+Light	4	36.82	6.07	0.03	0.97	-13.16
	Type+Turbid+Sal+pH+TN	6	37.68	6.93	0.02	0.99	-9.84
	NDVI+NDWI+NDBI+LST	5	40.25	9.5	0.01	1	-13.13

**Table 4. Occupancy models for nine predictor variables observed for *Polypedates leucomystax*.**

Variable categories	Predictors	K	AICc	Delta_AICc	AICcWt	Cum.Wt	LL
Local	pH+TN	3	33.2	0	0.35	0.35	-12.89
	Sal+pH+TN	4	36.28	3.09	0.08	0.91	-12.89
Landscape	LST+Light	3	33.85	0.65	0.26	0.61	-13.22
	NDVI+Light	3	34.1	0.9	0.23	0.83	-13.34
	NDVI+LST+Light	4	36.86	3.66	0.06	0.97	-13.18
	NDVI+NDWI+NDBI+LST	5	39.15	5.95	0.02	0.98	-12.58
	Type+Sal+pH+TN	5	39.75	6.56	0.01	1	-12.88
	Type+Turbid+Sal+pH+TN	6	43.7	10.51	0	1	-12.85
	Type+Turbid+Temp+Sal+pH+TN	7	47.9	14.7	0	1	-12.64

moisture (Basukriadi et al. 2021; Laurence et al. 2023).

*Polypedates leucomystax* probably is a fussy breeder in the urban city of Jakarta. Previous studies have documented the capability of this frog to utilize urban structures (Kuraishi et al. 2013; Shahrudin 2016). However, the quality of the man-made structures utilized by this frog is significantly different from *D.*

*melanostictus*. *Polypedates leucomystax* favours aged or senescent stagnant water with a low level of disturbances or modification to breed. Aged ponds often have stable water conditions, which are conducive to the growth of algae and microorganisms that serve as food sources for *P. leucomystax* larvae (Sandifer et al. 1993). In addition, our findings also highlighted the importance of landscape

factors in defining the breeding selection of this frog. *Polypedates leucomystax* is a tree frog, though this frog can adapt to man-made structures for laying eggs, *P. leucomystax* needs green areas to facilitate movement and other activities, especially for finding mates since this frog is solitary (Shahrudin 2016; Simon et al. 2022). Therefore, green connectivity is an important factor in supporting the breeding activities of *P. leucomystax* in urban environments.

Even though three common frog species documented in this study exhibit variation in preference for managed and unmanaged habitats, management criteria are not the best predictor explaining the habitat selection for breeding. Management state is probably not strongly associated with the local and landscape parameters required by frogs. Some managed habitats are capable of providing the resources and environmental conditions required by frogs to carry out breeding activities and safe habitats for the tadpoles. In contrast, unmanaged habitats in urban areas are probably not always safe for sensitive species to breed. Some of them are subjected to high exposure to water pollution such as heavy metals, or have potential risks of predators, especially fish. Most of the unmanaged habitats are linked strongly to wilderness habitats that are suitable for some other cryptic frogs that rely on low levels of ecological reset and enrichment.

Other frogs that are found in lower detection probably have similar basic requirements to other common frogs. Some of them (*F. cancrivora* and *F. limnocharis*) showed strong dependencies on paddy fields or related areas that were seemingly limited only to the urban periphery (Iskandar 1998; Kurniati 2006; Kurniati et al. 2010). In order to manage these species to persist in Jakarta, building paddy fields or related habitats scattered in the city of Jakarta is encouraged as well as providing connectivity among these areas. For *H. erythraea*, we recognized the challenging issue for urban planners and designers to maintain this frog. This frog is very sensitive to human disturbances and extreme temperatures, making this frog usually found in natural or rural areas located especially at medium levels of elevation. Temperature is likely the important factor that explains the presence of this species in Jakarta (Widyasamratri et al. 2019; Siswanto et al. 2023) since human disturbances are ubiquitous in Jakarta and the city's geographic location is at a low elevation. Therefore, urban planners and designers need to deal with urban heat islands as a general effort to maintain many areas in the city of Jakarta that are suitable for frog breeding and foraging activities.

Our findings indicate that all common frog species

residing in the urban landscape of Jakarta share different fundamental needs for their breeding habitats. Therefore, urban planning must take into account multiple criteria to ensure these habitats are preserved or created. Addressing these ecological requirements is essential not only for the survival of amphibian populations but also for achieving broader sustainable urban development goals, where biodiversity and natural habitats are integrated into the city's growth plans (Sedayu et al. 2024).

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Mr. Jatishwor Singh Irungbam, Biology Centre CAS, Branišovská, Czech Republic.  
Dr. Ian J. Kitching, Natural History Museum, Cromwell Road, UK  
Dr. George Mathew, Kerala Forest Research Institute, Peechi, India  
Dr. John Noyes, Natural History Museum, London, UK  
Dr. Albert G. Orr, Griffith University, Nathan, Australia  
Dr. Sameer Padhye, Katholieke Universiteit Leuven, Belgium  
Dr. Nancy van der Poorten, Toronto, Canada  
Dr. Kareen Schnabel, NIWA, Wellington, New Zealand  
Dr. R.M. Sharma, (Retd.) Scientist, Zoological Survey of India, Pune, India  
Dr. Manju Siliwal, WILD, Coimbatore, Tamil Nadu, India  
Dr. G.P. Sinha, Botanical Survey of India, Allahabad, India  
Dr. K.A. Subramanian, Zoological Survey of India, New Alipore, Kolkata, India  
Dr. P.M. Sureshan, Zoological Survey of India, Kozhikode, Kerala, India  
Dr. R. Varatharajan, Manipur University, Imphal, Manipur, India  
Dr. Eduard Vives, Museu de Ciències Naturals de Barcelona, Terrassa, Spain  
Dr. James Young, Hong Kong Lepidopterists' Society, Hong Kong  
Dr. R. Sundararaj, Institute of Wood Science & Technology, Bengaluru, India  
Dr. M. Nithyanandan, Environmental Department, La Ala Al Kuwait Real Estate. Co. K.S.C., Kuwait  
Dr. Himender Bharti, Punjabi University, Punjab, India  
Mr. Purnendu Roy, London, UK  
Mr. Saito Motoki, The Butterfly Society of Japan, Tokyo, Japan  
Dr. Sanjay Sondhi, TITLI TRUST, Kalpavriksh, Dehradun, India  
Dr. Nguyen Thi Phuong Lien, Vietnam Academy of Science and Technology, Hanoi, Vietnam  
Dr. Nitin Kulkarni, Tropical Research Institute, Jabalpur, India  
Dr. Robin Wen Jiang Ngiam, National Parks Board, Singapore  
Dr. Lionel Monod, Natural History Museum of Geneva, Genève, Switzerland.  
Dr. Asheesh Shivam, Nehru Gram Bharti University, Allahabad, India  
Dr. Rosana Moreira da Rocha, Universidade Federal do Paraná, Curitiba, Brasil  
Dr. Kurt R. Arnold, North Dakota State University, Saxony, Germany  
Dr. James M. Carpenter, American Museum of Natural History, New York, USA  
Dr. David M. Claborn, Missouri State University, Springfield, USA  
Dr. Kareen Schnabel, Marine Biologist, Wellington, New Zealand  
Dr. Amazonas Chagas Júnior, Universidade Federal de Mato Grosso, Cuiabá, Brasil  
Mr. Monsoon Jyoti Gogoi, Assam University, Silchar, Assam, India  
Dr. Heo Chong Chin, Universiti Teknologi MARA (UiTM), Selangor, Malaysia  
Dr. R.J. Shiel, University of Adelaide, SA 5005, Australia  
Dr. Siddharth Kulkarni, The George Washington University, Washington, USA  
Dr. Priyadarsanan Dharma Rajan, ATREE, Bengaluru, India  
Dr. Phil Alderslade, CSIRO Marine And Atmospheric Research, Hobart, Australia  
Dr. John E.N. Veron, Coral Reef Research, Townsville, Australia  
Dr. Daniel Whitmore, State Museum of Natural History Stuttgart, Rosenstein, Germany.  
Dr. Yu-Feng Hsu, National Taiwan Normal University, Taipei City, Taiwan  
Dr. Keith V. Wolfe, Antioch, California, USA  
Dr. Siddharth Kulkarni, The Hormiga Lab, The George Washington University, Washington, D.C., USA  
Dr. Tomas Ditrich, Faculty of Education, University of South Bohemia in Ceske Budejovice, Czech Republic  
Dr. Mihaly Foldvari, Natural History Museum, University of Oslo, Norway  
Dr. V.P. Uniyal, Wildlife Institute of India, Dehradun, Uttarakhand 248001, India  
Dr. John T.D. Caleb, Zoological Survey of India, Kolkata, West Bengal, India  
Dr. Priyadarsanan Dharma Rajan, Ashoka Trust for Research in Ecology and the Environment (ATREE), Royal Enclave, Bangalore, Karnataka, India

#### Fishes

Dr. Topiltzin Contreras MacBeath, Universidad Autónoma del estado de Morelos, México  
Dr. Heok Hee Ng, National University of Singapore, Science Drive, Singapore  
Dr. Rajeesh Raghavan, St. Albert's College, Kochi, Kerala, India  
Dr. Robert D. Sluka, Chiltern Gateway Project, A Rocha UK, Southall, Middlesex, UK  
Dr. E. Vivekanandan, Central Marine Fisheries Research Institute, Chennai, India  
Dr. Davor Zanella, University of Zagreb, Zagreb, Croatia  
Dr. A. Biju Kumar, University of Kerala, Thiruvananthapuram, Kerala, India  
Dr. Akhilesh K.V., ICAR-Central Marine Fisheries Research Institute, Mumbai Research Centre, Mumbai, Maharashtra, India  
Dr. J.A. Johnson, Wildlife Institute of India, Dehradun, Uttarakhand, India  
Dr. R. Ravinesh, Gujarat Institute of Desert Ecology, Gujarat, India

#### Amphibians

Dr. Sushil K. Dutta, Indian Institute of Science, Bengaluru, Karnataka, India  
Dr. Annemarie Ohler, Muséum national d'Histoire naturelle, Paris, France

#### Reptiles

Dr. Gernot Vogel, Heidelberg, Germany  
Dr. Raju Vyasa, Vadodara, Gujarat, India  
Dr. Pritpal S. Soorae, Environment Agency, Abu Dhabi, UAE.  
Prof. Dr. Wayne J. Fuller, Near East University, Mersin, Turkey  
Prof. Chandrashekhar U. Rivonker, Goa University, Taleigao Plateau, Goa, India  
Dr. S.R. Ganesh, Kalinga Foundation, Agumbe, India.  
Dr. Himansu Sekhar Das, Terrestrial & Marine Biodiversity, Abu Dhabi, UAE

#### Birds

Dr. Hem Sagar Baral, Charles Sturt University, NSW Australia  
Mr. H. Byju, Coimbatore, Tamil Nadu, India  
Dr. Chris Bowden, Royal Society for the Protection of Birds, Sandy, UK  
Dr. Priya Davidar, Pondicherry University, Kalapet, Puducherry, India  
Dr. J.W. Duckworth, IUCN SSC, Bath, UK  
Dr. Rajah Jayapal, SACON, Coimbatore, Tamil Nadu, India  
Dr. Rajiv S. Kalsi, M.L.N. College, Yamuna Nagar, Haryana, India  
Dr. V. Santharam, Rishi Valley Education Centre, Chittoor Dt., Andhra Pradesh, India  
Dr. S. Balachandran, Bombay Natural History Society, Mumbai, India  
Mr. J. Praveen, Bengaluru, India  
Dr. C. Srinivasulu, Osmania University, Hyderabad, India  
Dr. K.S. Gopi Sundar, International Crane Foundation, Baraboo, USA  
Dr. Gombobaatar Sundev, Professor of Ornithology, Ulaanbaatar, Mongolia  
Prof. Reuven Yosef, International Birding & Research Centre, Eilat, Israel  
Dr. Taej Mundkur, Wetlands International, Wageningen, The Netherlands  
Dr. Carol Inskipp, Bishop Auckland Co., Durham, UK  
Dr. Tim Inskipp, Bishop Auckland Co., Durham, UK  
Dr. V. Gokula, National College, Tiruchirappalli, Tamil Nadu, India  
Dr. Arkady Lelej, Russian Academy of Sciences, Vladivostok, Russia  
Dr. Simon Dowell, Science Director, Chester Zoo, UK  
Dr. Mário Gabriel Santiago dos Santos, Universidade de Trás-os-Montes e Alto Douro, Quinta de Prados, Vila Real, Portugal  
Dr. Grant Connette, Smithsonian Institution, Royal, VA, USA  
Dr. P.A. Azeez, Coimbatore, Tamil Nadu, India

#### Mammals

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Tamil Nadu 641006, India  
ravi@threatenedtaxa.org & ravi@zooreach.org



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