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Predicting potential traps in drainage systems

A GIS-based approach in amphibian conservation

submitted by

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Finally, I want to thank my family who has supported and encouraged me throughout the entire process.

SCIENCE PLEDGE

I hereby declare that I have independently completed this Master's thesis. All sources used are fully and correctly listed in the bibliography. This thesis has not been submitted in any previous procedure and has not been accepted by any other institution.

While working on this thesis, I used ChatGPT-4 (Version 2) enhance the writing style and check for spelling and grammar errors. I take full responsibility for everything presented in this work.

Winterthur, 24.11.2024 Cristina Piccirillo

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ABSTRACT

Urban drainage systems, specifically gully pots, represent significant risks to amphibian populations as they can be potential traps for individuals and lead to unnatural mortality. In this study, I tested a GIS-based approach to predict potential amphibian traps in drainage systems using abundance data collected in the city of Zurich. I applied linear regression models to identify environmental factors influencing the abundance of six amphibian species found in gully pots, including the common frog (*Rana temporaria*), common toad (*Bufo bufo*), alpine newt (*Ichthyosaura alpestris*), fire salamander (*Salamandra salamandra*), palmate newt (*Lissotriton helveticus*), and water frog (*Pelophylax sp.*). I found that proximity to stagnant water bodies and past amphibian observations are significant factors influencing amphibian abundance in gully pots, while urbanization, particularly the presence of buildings, negatively impacts amphibian abundance. The results for each species can be used to predict amphibian abundance in gully pots, contributing to the improvement of targeted conservation measures, such as the use of amphibian escape ladders.

1. INTRODUCTION

1.1. SPECIES DISTRIBUTION MODELS

A key goal in ecology is to model and understand the relationship between species and their environment (Guisan and Zimmermann 2000, Rushton, Ormerod et al. 2004). Spatial distribution models (SDM) are usually used for this purpose (Araújo and Guisan 2006). The growing availability of digital data and user-friendly software has contributed to a notable increase in SDM research in recent decades (Zurell, Franklin et al. 2020). Nowadays, GIS-tools make it possible to analyze large spatial databases and easily extract potential predictor variables. Statistical methods, like linear regression, generalized linear models (GLM) and generalized additive models (GAM), are utilized to identify the factors influencing the response variable and to build predictive models (Guisan and Zimmermann 2000).

Amphibians are often the focus of species distribution models because they are among the most threatened animal groups. Due to their dependency on specific aquatic habitats, their limited ranges and sensitivity to environmental changes, amphibians are particularly vulnerable to threats like climate change and habitat loss. Understanding their distribution and habitat preferences is crucial for developing effective conservation plans. Many studies have examined how the composition of landscapes near water bodies affects the likelihood of amphibian presence (Herrmann, Babbitt et al. 2005, Johansson, Primmer et al. 2005, Houlahan, Keddy et al. 2006, Gagné and Fahrig 2007). For example, Herrmann, Babbitt et al. (2005) found that the amount of forest cover within 1000 m of the wetland may have a significant impact on the diversity of larval amphibian communities. Similarly, Johansson, Primmer et al. (2005) investigated the impact of landscapes influenced by agriculture on the presence, abundance, and genetic diversity of the common frog (*Rana temporaria*). They found distinct, but regionally contrasting effects of habitat composition on both population size and genetic diversity in amphibian populations. Gagné and Fahrig (2007) compared the relative effects of urban, agricultural, and forested landscapes on amphibian species richness and the abundance of individual amphibian species found at breeding ponds. Their results indicated that ponds in urban landscapes showed the lowest diversity in anuran species. Other studies show the negative effect of road density on anuran populations – it is at least as great as the negative effect of deforestation (Eigenbrod, Hecnar et al. 2008). All these studies suggest that landscape changes due to human activities lead to a loss of suitable habitats and connectivity between populations. This can disturb important population processes and ultimately impact the survival of amphibian populations.

However, amphibians often live in human-made environments, including urban areas. There, they face numerous risks that lead to unnatural mortality – among them, traps like gully pots. To protect these vulnerable species, it is essential to address these risks, beginning with identifying the location of these traps and determine which of these represent a major risk to amphibians. Spatial distribution models can be used to make predictions on the likelihood of amphibian presence and abundance in gully pots. It is expected that the probability of finding a specific species in a gully pot depends on whether it is located within or near the preferred habitat of the species. Distance to known neighboring still waters and observations of the amphibian species in the past should also be taken into account (Moilanen and Nieminen 2002). By applying predictive species distribution models, decision-makers can effectively prioritize and plan conservation measures.

1.2. AMPHIBIAN ESCAPE LADDERS

According to the red list of endangered species in Switzerland, 14 out of 19 amphibian species are considered potentially endangered (Schmidt, Mermod et al. 2023). The decline of many amphibian species is often linked to spatial factors such as habitat loss caused by the intensification of forestry and agriculture, as well as the increasing fragmentation and isolation of their habitats (Meyer, Zumbach et al. 2009, Downie, Larcombe et al. 2019). An often underestimated factor is mortality caused by road traffic (Glista, DeVault et al. 2008). As the human population increases, so does the demand for transportation, leading to more roads and more traffic. For amphibians, which often have to cross roads during their migrations to their breeding sites or back to their winter quarters are often killed by vehicles (McInroy and Rose 2015, Downie, Larcombe et al. 2019). Collisions can also occur when amphibians venture across roads within their habitats in search of food. When crossing roads, the animal not only puts itself at risk of being run over by vehicles but also of falling into gully pots. Curbs over 3 cm pose an obstacle for amphibians and therefore have a guiding effect: amphibians migrate along the curb, cross multiple gully pots and often fall into them (McInroy and Rose 2015, Angelone 2021). Once amphibians become trapped in gully pots, they often starve or get into the sewer network, eventually ending up in the nearest sewage treatment plant (Angelone 2021). Grün Stadt Zürich (GSZ) is a service unit of the Department of Civil Engineering and Waste Management of the City of Zurich. In a multi-year study, they were able to demonstrate that the presence and consequently the mortality of amphibians in gully pots can be significantly reduced by installing amphibian ladders (Angelone 2021).

FIGURE 1: LEFT PICTURE: COMMON FROG CLIMBING OUT OF THE GULLY POT USING AN AMPHIBIAN LADDER, RIGHT PICTURE: MONITORING OF GULLY POTS IN ZURICH.

McInroy and Rose (2015) also found a significantly lower number of trapped amphibians in gully pots with installed amphibian ladders compared to gully pots without escape exit aids. However, with several thousand drains per municipality, the question arises as to which gully pots should be prioritized for the installation of escape ladders and in which areas the maintenance of the applied measures should be prioritized. Grün Stadt Zürich (GSZ) defined amphibian zones based on various criteria, including amphibian populations, ecologically valuable areas, and connectivity corridors. Within these zones, amphibian ladders were installed in gully pots. It would be interesting to investigate whether other, unexpected environmental factors influence the presence of amphibians in these gully pots.

1.3. RESEARCH AIM AND OBJECTIVES

The aim of this study is to determine which environmental variables influence the likelihood of finding a specific amphibian species in gully pots. For statistical analysis, I used abundance data collected by GSZ. The data consist of counts of various native amphibian species, most of which were included in the study.

For each of the examined gully pot, I determined proportions of different ground cover types within multiple buffers (100, 200, 500 and 1000 m) around the location. I computed the weighted sum of proportions over all buffer radii to get one variable per ground cover type. Additionally, I determined connectivity measures such as the distance to known water bodies or amphibian sightings.

Based on findings from the literature, the abundance of each individual amphibian species is expected to be lower in gully pots located in urban areas than in agricultural or forested areas. Furthermore, it is expected that the proximity of water bodies positively affects the abundance of amphibians in gully pots.

2. METHODS

2.1. ABUNDANCE DATA

GSZ conducted a multi-year study on the effectiveness of amphibian ladders. Each year, a certain number of gully pots located in areas in the city of Zurich where amphibian presence is expected were examined in a systematic, staged approach. For each gully pot, the number of amphibians and their species were noted. From 2009 to 2020, a total of 4429 amphibians were found in 1826 gully pots without amphibian ladders, with 96 of them being dead (Angelone 2021).

At that time, only presences (and abundance) were recorded, so I do not exactly know today which gully pots were additionally examined and where no amphibians were found. Hence, there is no absence (or rather non-detection) data.

To obtain the absence (or non-detection) data and enhance the statistical power of the study, I worked with one of the project's biologists to reconstruct the study areas in a Geographic Information System (GIS). I carefully digitized the original study areas based on field data and information provided by the biologist and saved these reconstructed areas as a dedicated layer in the GIS (Figure 2). Using spatial analysis tools within the GIS, I then calculated the total number of gully pots within these reconstructed study areas, which turned out to be quite substantial, totaling 8733 gully pots. With the exact locations of all gully pots within the study areas identified, I was able to determine which gully pots had been examined during the study.

Once all examined gully pots were identified, I compared them with the observation data to pinpoint those gully pots where no amphibians were detected, despite being surveyed. These gully pots were then classified as absence data (or non-detection data) and included in the analysis. Incorporating these absence data significantly improved the statistical power of the study, allowing for a more precise modeling of amphibian distribution across the gully pots and a better understanding of the factors influencing their abundance.

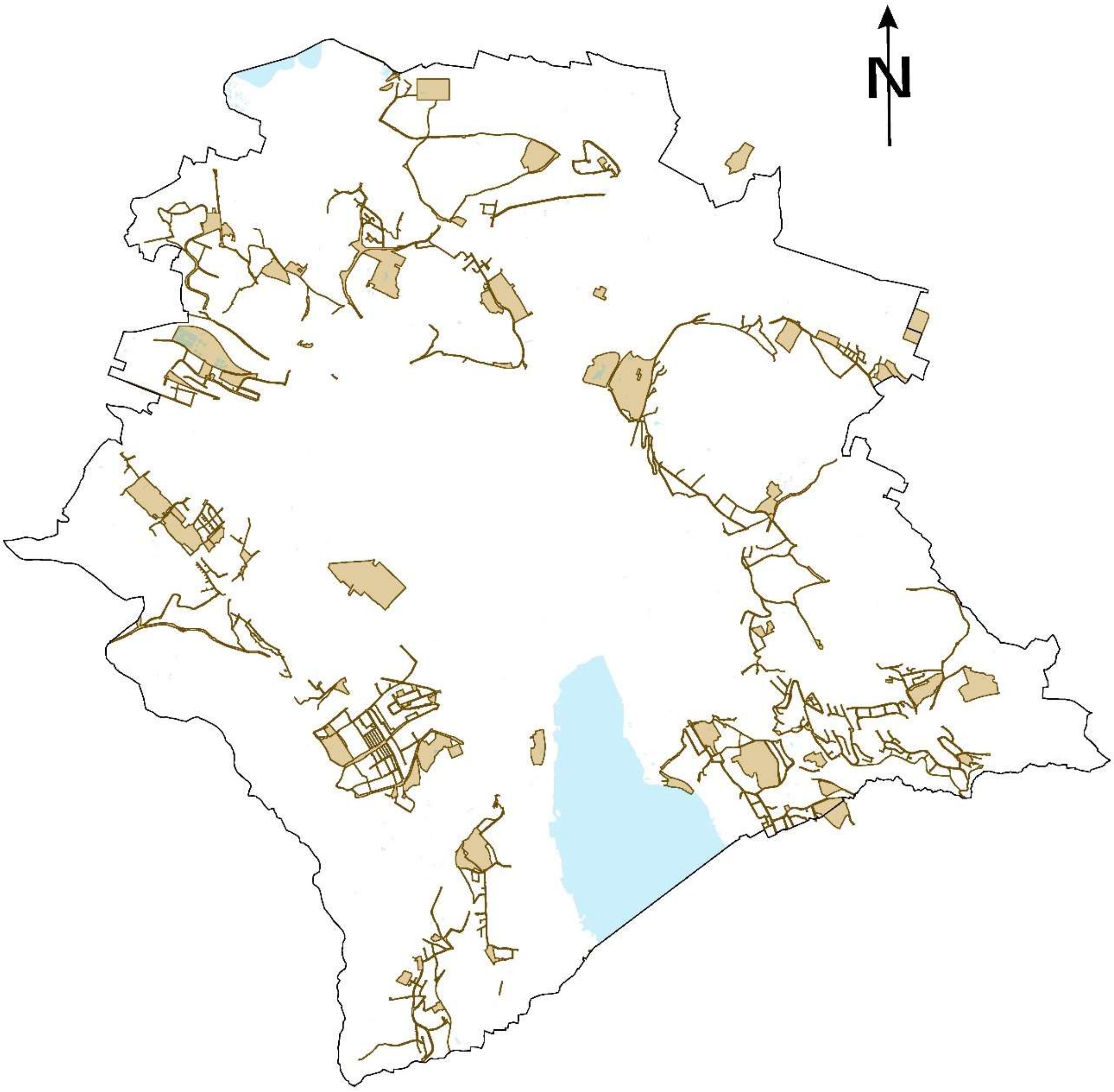


FIGURE 2: MAP DISPLAYING THE RECONSTRUCTED STUDY AREAS IN ZURICH.

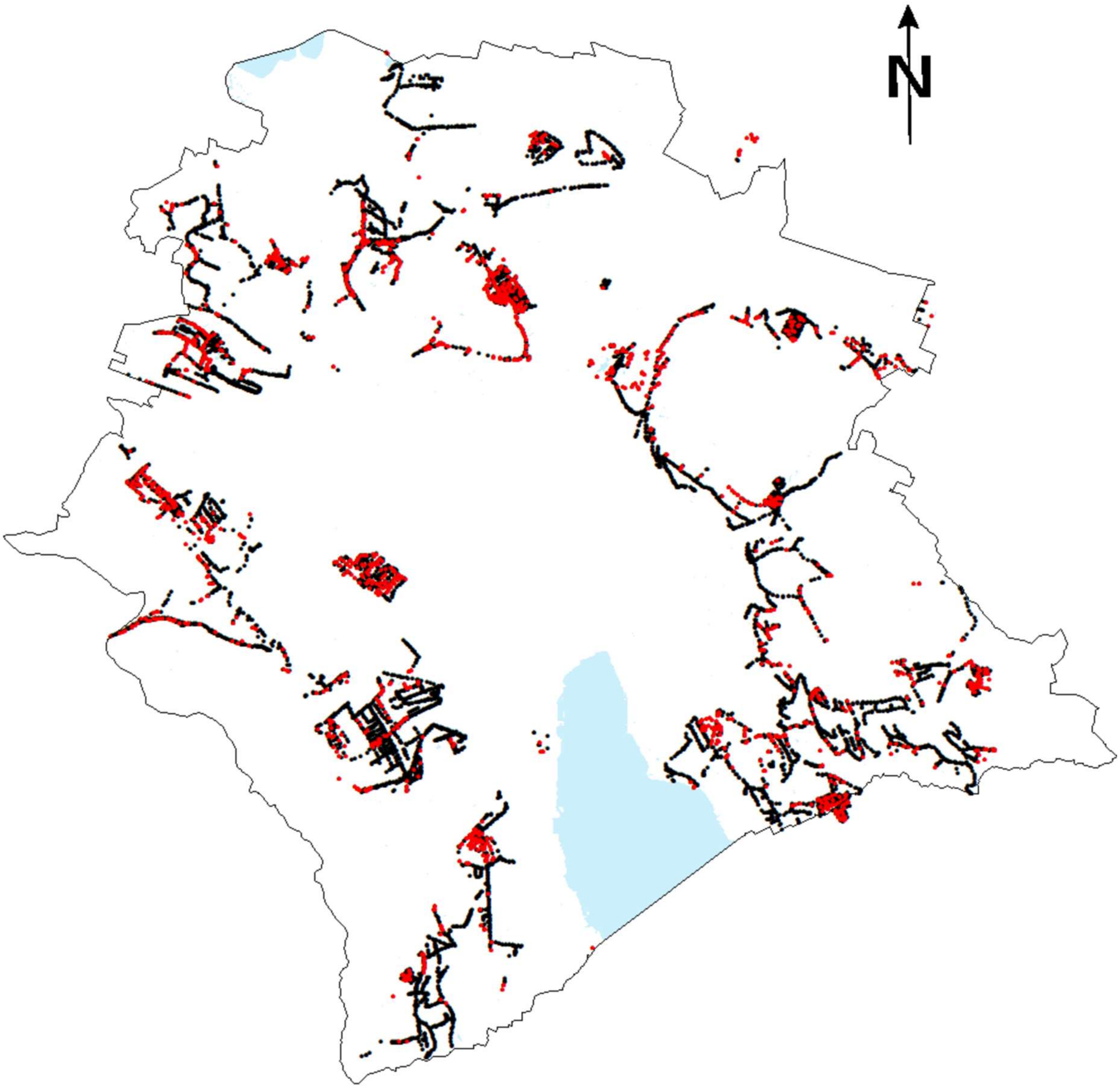


FIGURE 3: MAP OF ZURICH SHOWING THE EXAMINED GULLY POTS. THE RED MARKERS INDICATE THE GULLY POTS WERE AMPHIBIANS WERE DETECTED, WHILE THE BLACK MARKERS REPRESENT THE GULLY POTS WHERE NO AMPHIBIANS WERE FOUND.

2.2. ENVIRONMENTAL VARIABLES

The geographical data used in this analysis consists of the ground cover layers derived from the official survey of Switzerland. The Swiss government sets the level of detail in the ground cover data, ensuring its relatively high accuracy and continuous updates. Only ground cover areas surpassing a minimum size, dependent on the specific type of ground cover, are recorded (KKVA 2019). Nevertheless, multiple studies have demonstrated that even spatially coarse data can be suitable for estimating amphibian abundance or presence at specific locations (Knutson, Sauer et al. 1999, Joly, Miaud et al. 2001, Johansson, Primmer et al. 2005, Zanini, Pellet et al. 2009), which led me to conduct our analysis using this data. Another reason for this choice is the availability - while ground cover data may be coarse, more fine-grained data is not always accessible and often requires additional efforts to obtain, such as digitalizing through aerial imagery.

Furthermore, ground cover data offers distinct advantages over aerial images: it reveals sealed areas such as forest paths or roads without obstruction from vegetation, it remains free from spatial distortion, and the proportions remain accurate regardless of elevation.

According to the federal INTERLIS data model DM.01-AV-CH the following ground cover types are distinguished: buildings, sealed surfaces, humus-rich areas, water bodies, wooded areas, bare areas (Figure 4, Appendix 1).

For each of the examined gully pots, the proportions of the ground cover types within concentric buffers are determined at different spatial scales. Different radii are considered for this purpose (100, 200, 500 and 1000 m). For each ground cover type, the proportions are distance-weighted, and the weighted proportions are summed up to a single predictor variable (Table 1). Distance weighting is done according to the inverse square formula.

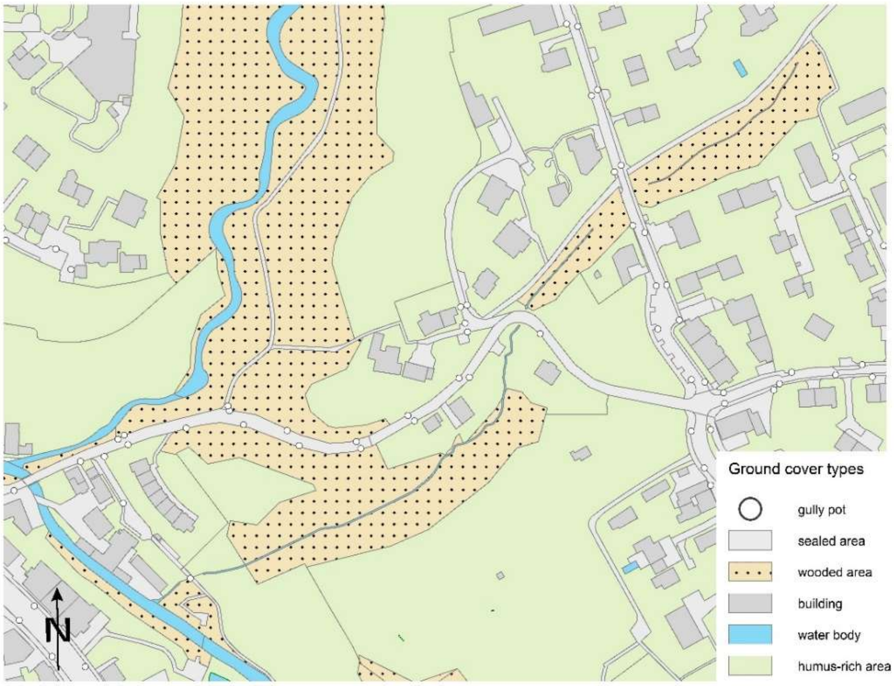


FIGURE 4: MAP SHOWING THE DIFFERENT CATEGORIES OF LAND COVER FROM THE SWISS OFFICIAL SURVEY

TABLE 1: PREDICTOR VARIABLES USED FOR MODELLING THE AMPHIBIAN ABUNDANCE IN GULLY POTS.

Variable	Definition
SP_sealed	Sum of the weighted proportions of sealed surfaces
SP_wooded	Sum of the weighted proportions of wooded areas
SP_water	Sum of the weighted proportions of water bodies
SP_buildings	Sum of the weighted proportions of buildings
SP_humus	Sum of the weighted proportions of humus-rich areas
SP_vegfree	Sum of the weighted proportions of vegetation-free areas
Anz_Gew1k	Number of stagnant water bodies in a 1000m radius
min_Dist	Shortest distance to the nearest stagnant water body within a 1000m radius (in meters)
Obsv_BB_1k	Number of common toad *(Bufo bufo)* observations within a 1000m radius
minDist_BB	Shortest distance to the nearest common toad *(Bufo bufo)* observation within a 1000 m radius
Obsv_RT_1k	Number of common frog *(Rana temporaria)* observations within a 1000m radius
minDist_RT	Shortest distance to the nearest common frog *(Rana temporaria)* observation within a 1000m radius
Obsv_IA_1k	Number of alpine newt *(Ichthyosaura alpestris)* observations within a 1000m radius
minDist_IA	Shortest distance to the nearest alpine newt *(Ichthyosaura alpestris)* observation within a 1000m radius
Obsv_SS_1k	Number of fire salamander *(Salamandra salamandra)* observations within a 1000m radius
minDist_SS	Shortest distance to the nearest fire salamander *(Salamandra salamandra)* observation within a 1000m radius
Obsv_LH_1k	Number of palmate newt *(Lissotriton helveticus)* observations within a 1000m radius
minDist_LH	Shortest distance to the nearest palmate newt *(Lissotriton helveticus)* observation within a 1000m radius
Obsv_PS_1k	Number of water frog *(Pelophylax sp.)* observations within a 1000m radius
minDist_PS	Shortest distance to the nearest water frog *(Pelophylax sp.)* observation within a 1000m radius

The analysis of geographical data was conducted using the Spatial Modeler tool from Hexagon.

2.3. STATISTICAL ANALYSIS

For each species found during the surveys, I examined potential spatial autocorrelation in the response variable (abundance) using the Moran’s index as a function of spatial distance. Moran’s index is interpreted as follows: A positive value indicates that the analyzed data is rather clustered, while a negative value suggests dispersion. Values around zero mean that the spatial arrangement is random.

To test the hypothesis that species abundance is randomly distributed across all surveyed gully pots, I ran a Monte Carlo simulation with 9999 permutations, and the p-value was calculated. I extended this analysis by computing Moran's I statistics at different distance bands to analyze spatial autocorrelation as a function of distance. Moran's I statistics were computed using the R statistical software (version 4.3.1, R Core Team) with the 'spdep' package (Bivand, Bernat et al. 2005).

I used linear models to identify the variables that best explain the amphibian abundance in gully pots. The dependent variable (abundance) was log-transformed (log10[x+1]), and I used z-score standardization to normalize continuous predictor variables.

For model selection, I applied the dredge() function from the MuMIn package in R (Barton 2020). This function generates all possible subsets of a global model that includes all predictor variables. All resulting models are evaluated and ranked using the Akaike Information Criterion (AIC), with the best models having the lowest AIC-value. The dredge() function is particularly useful in studies where multiple predictors need to be evaluated simultaneously, and the goal is to identify the most parsimonious model or models that best explain the observed data. This method can be used in situations where there is uncertainty about which predictor variables should be included in the model, allowing to explore all possible combinations systematically (Barton 2020).

As I found a low spatial autocorrelation in the data, I added the geographical coordinates (x and y) to the full models for the dredge analysis. The geographical coordinates are only tested as combination.

Given the possible interdependence of ground cover proportions, I performed correlation analyses and avoided using correlated variables in the models to reduce collinearity effects. Additionally, I calculated generalized variance inflation factors (GVIF) for the top-ranked models as an additional collinearity test.

3. RESULTS

3.1. AMPHIBIAN ABUNDANCE

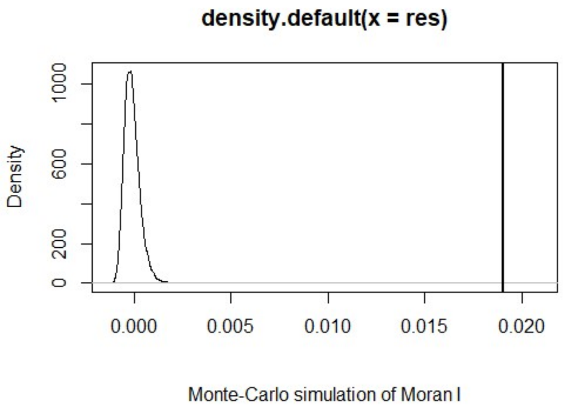
The most found amphibian species in the gully pots were the common toad (1534), the common frog (1661), and the alpine newt (783). Fire salamanders and water frogs (pool frogs, edible frogs, marsh frogs) followed with 101 and 143 individuals found respectively. Yellow-bellied toads and midwife toads were only found in isolated cases (2 and 4 respectively) and are therefore excluded from the analysis.

3.2. SPATIAL AUTOCORRELATION

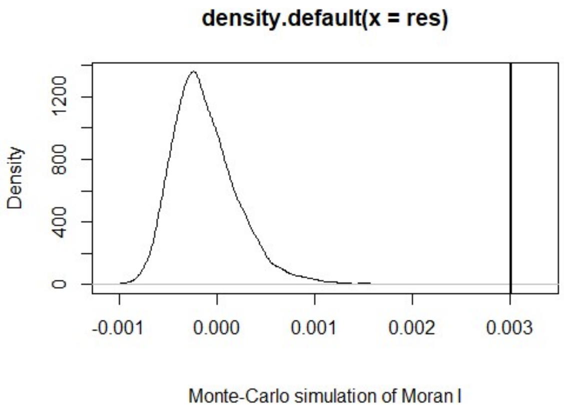
The Moran's I Monte Carlo simulation resulted in low Moran’s I values for all amphibian species. The density function shows the distribution of Moran's I values that would be expected if the abundance were randomly distributed across all gully pots. The vertical line in the plots show the observed Moran’s I (Figure 5). The observed Moran’s I statistics fall to the right of the distributions, which suggests that the abundances are clustered (a positive Moran's I value suggests clustering whereas a negative Moran's I value suggests dispersion). However, the Moran’s I values close to zero indicate a weak spatial correlation, even though the p-values may suggest statistical significance.

The Moran’s I correlograms which show the Moran’s I values as a function of distance didn’t show a constant decline for species abundance (Figure 6). In almost all cases, spatial correlation is strong at short distances but rapidly decreases, indicating a high likelihood of finding the same species in neighboring gully pots.

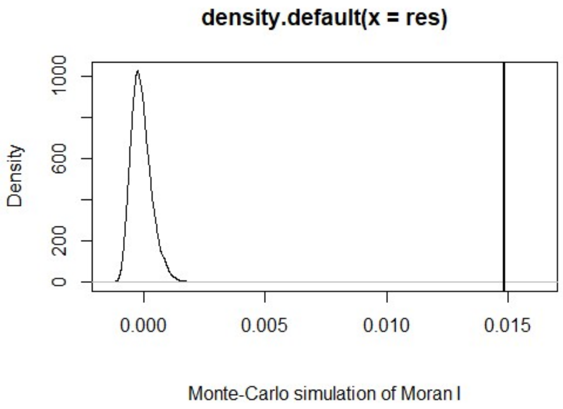
Common frog *(Rana temporaria)*
Moran’s I = 0.0190
p-value = 0.0001



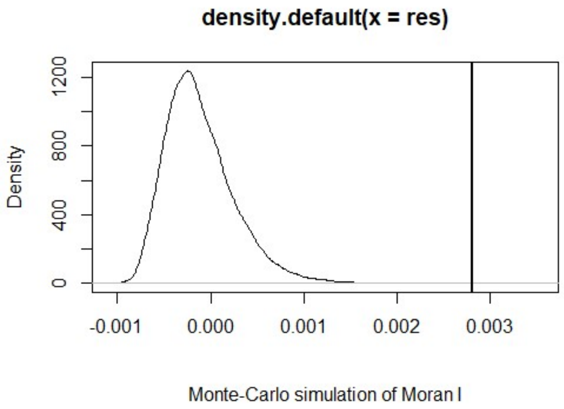
Fire salamander *(Salamandra salamandra)*
Moran’s I = 0.0030
p-value = 0.0001



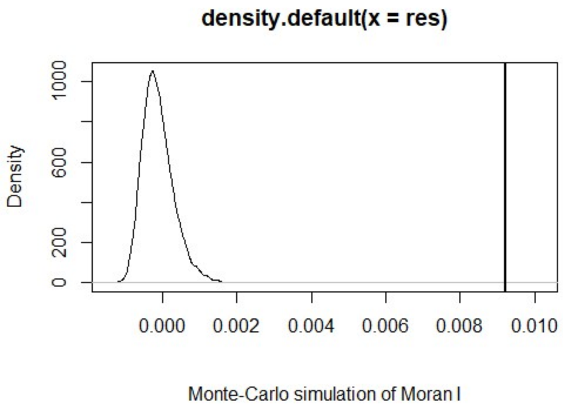
Common toad *(Bufo bufo)*
Moran’s I = 0.0149
p-value = 0.0001



Palmate newt *(Lissotriton helveticus)*
Moran’s I = 0.0028
p-value = 0.0001



Alpine newt *(Ichthyosaura alpestris)*
Moran’s I = 0.0092
p-value = 0.0001



Water frog *(Pelophylax agg.)*
Moran’s I = 0.0030
p-value = 0.0001

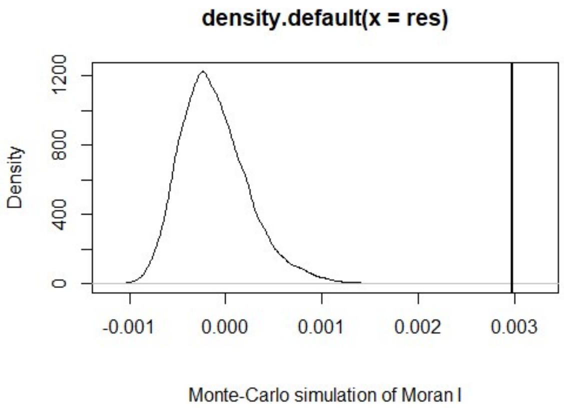
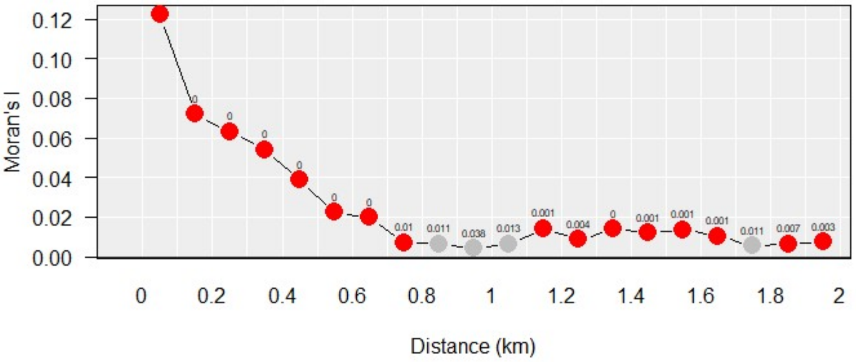
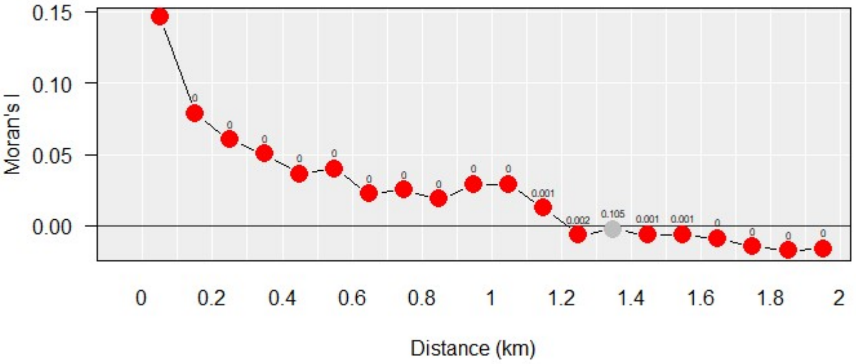


FIGURE 5: RESULTS OF THE MONTE-CARLO SIMULATION OF MORAN I

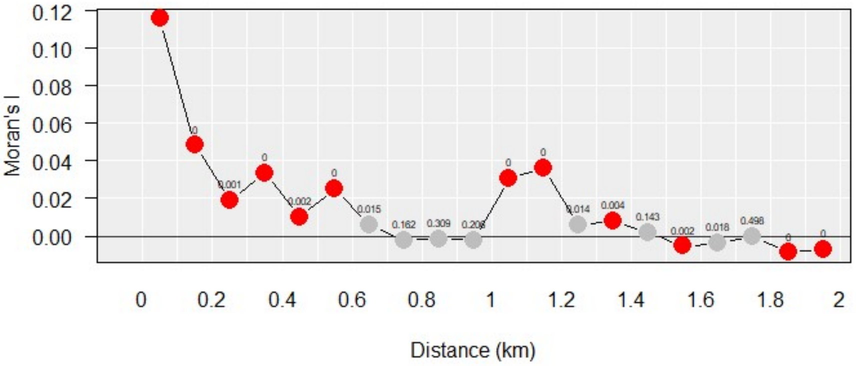
Common frog *(Rana temporaria)*



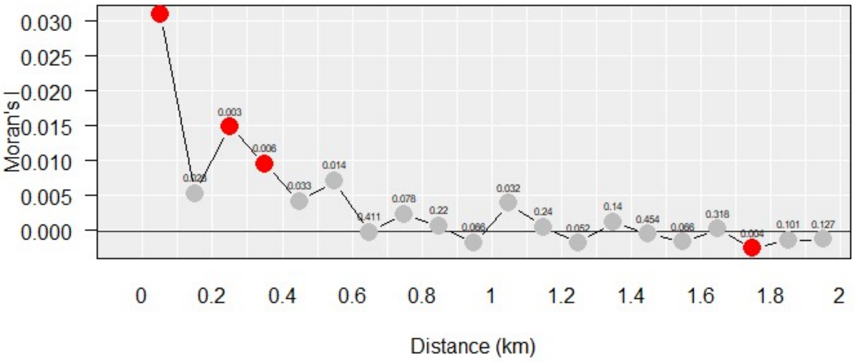
Common toad *(Bufo bufo)*



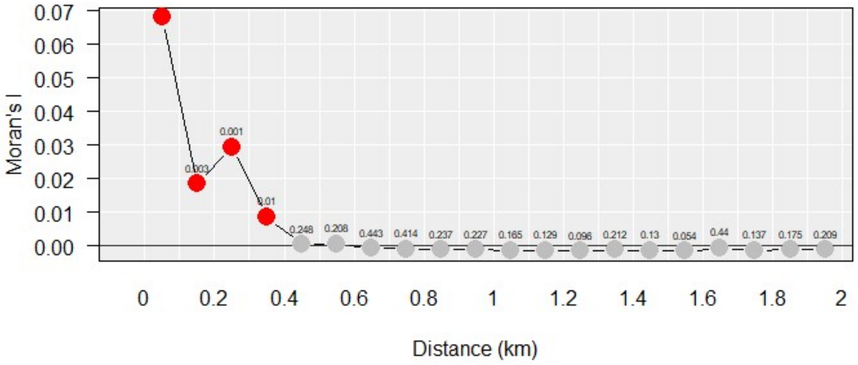
Alpine newt *(Ichthyosaura alpestris)*



Fire Salamander *(Salamandra salamandra)*



Palmate newt *(Lissotriton helveticus)*



Water frog *(Pelophylax agg.)*

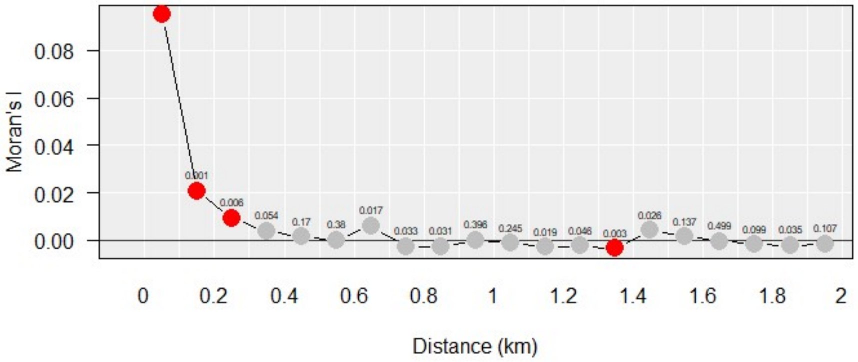


FIGURE 6: MORAN'S I STATISTICS AS A FUNCTION OF DISTANCE BANDS. THE RED DOTS REPRESENT STATISTICALLY SIGNIFICANT MORAN'S I VALUES ($P < 0.01$).

3.3. MODEL SELECTION

As the proportion of vegetation-free areas was negligible, I excluded this variable from the statistical analysis (only 23 out of 8733 gully pots had vegetation-free areas within their 500m buffer). Furthermore, I observed a strong positive correlation between the proportion of sealed surfaces and the proportion of buildings (r=0.7). There is also a strong negative correlation (r= -0.63) between the proportion of sealed surfaces and the proportion of wooded areas. Consequently, in testing the models, I avoided using combinations of these variables.

The best models were selected primarily based on the AIC (Akaike Information Criterion) value. When the difference in AIC values between the top models is very small (typically a ΔAIC less than 2), it suggests that multiple models are similarly supported by the data. In such cases, the simpler model was chosen as the best model. The models best explaining the abundance for each species are shown in the table below.

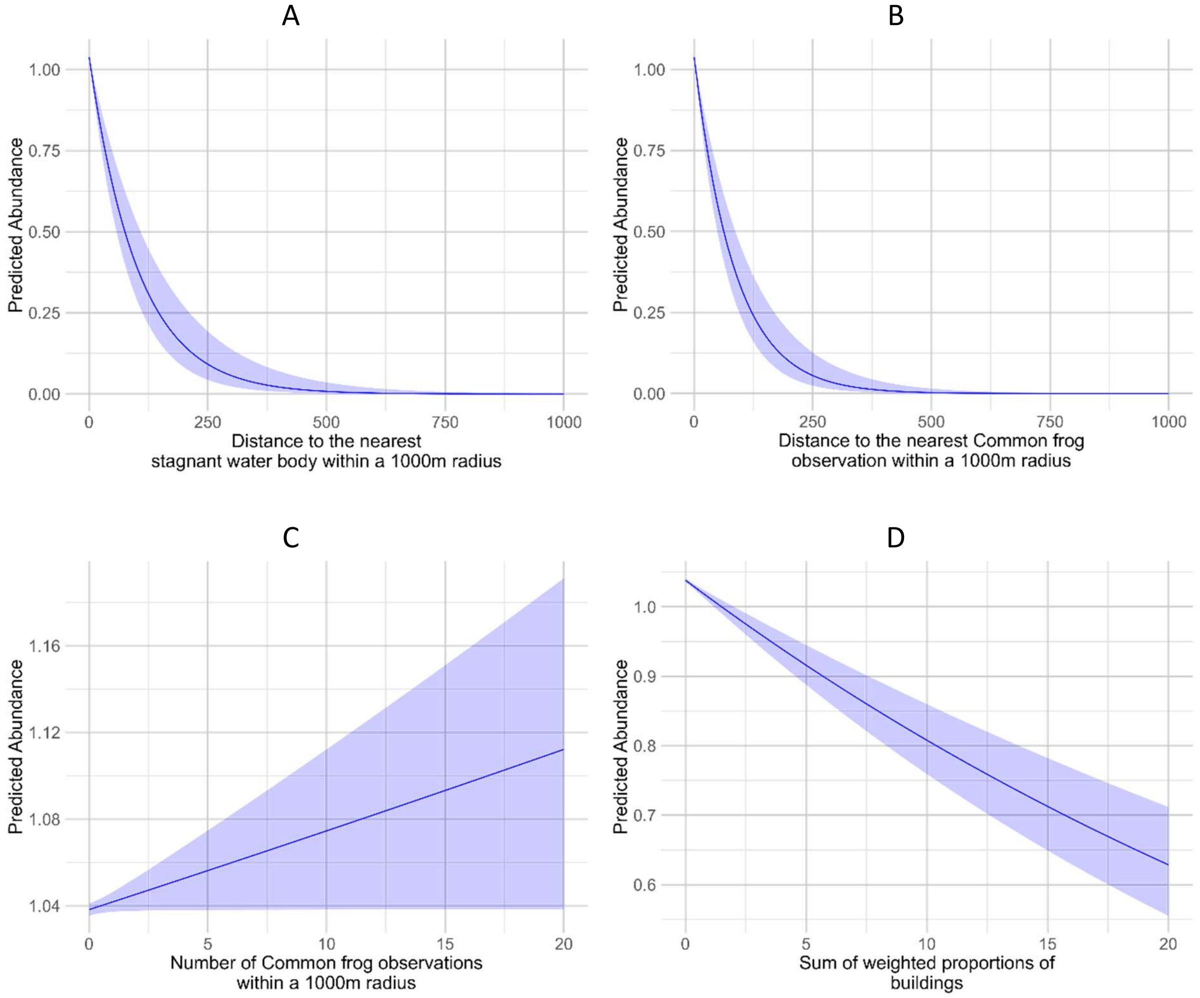
TABLE 2: SUMMARY OF THE LINEAR MODELS BEST EXPLAINING ABUNDANCE DATA FOR EACH SPECIES.

Species	Variable	Estimate	Std.Error	p-value	GVIF
Common frog ***(Rana temporaria)***	Intercept	-11.970000	1.801000	3.16e-11***	-
	min_Dist_sc	-0.009715	0.001519	1.68e-10***	1.0780
	minDist_RT_sc	-0.011720	0.001682	3.43e-12***	1.1775
	Obsv_RT_1k_sc	0.003437	0.001748	0.0493*	1.2406
	SP_wooded_sc	-0.010530	0.003883	0.0067**	2.7553
	SP_buildings_sc	-0.025090	0.003170	2.75e-15***	2.2497
	SP_water_sc	-0.004342	0.001841	0.0183 *	1.3061
	SP_humus_sc	-0.016970	0.003013	1.85e-08***	2.1384
	x_coord	0.000003	0.000001	5.43e-06***	1.1545
	y_coord	0.000004	0.000001	3.13e-14***	1.0845
Common toad ***(Bufo bufo)***	Intercept	4.733000	1.627000	0.003630 **	-
	Anz_Gew1k_sc	-0.005968	0.001932	0.002018 **	1.4293
	min_Dist_sc	-0.012290	0.001458	< 2e-16***	1.0784
	minDist_BB_sc	-0.011750	0.001498	4.88e-15***	1.1060
	Obsv_BB_1k_sc	0.011260	0.001656	1.13e-11***	1.2252
	SP_buildings_sc	-0.015860	0.001403	< 2e-16***	1.0379
	SP_water_sc	-0.008950	0.001410	2.31e-10***	1.0431
	x_coord	-0.000002	0.000001	0.000128 ***	1.0839
	y_coord	0.000000	0.000001	0.428674	1.2740
Alpine newt ***(Ichthyosaura alpestris)***	Intercept	1.851000	1.206000	0.124796	-
	Anz_Gew1k_sc	-0.008998	0.001349	2.76e-11***	1.3325
	min_Dist_sc	-0.008026	0.001104	3.93e-13***	1.0901
	minDist_IA_sc	-0.008625	0.001125	1.98e-14***	1.1110
	SP_wooded_sc	-0.003741	0.001336	0.005106 **	1.3188
	SP_buildings_sc	-0.007388	0.001407	1.57e-07***	1.3897
	x_coord	0.000000	0.000000	0.981864	1.0844
	y_coord	-0.000001	0.000000	0.000868 ***	1.2674
Fire salamander ***(Salamandra salamandra)***	Intercept	1.686000	0.452000	0.000193 ***	-
	Anz_Gew1k_sc	-0.000935	0.000485	0.053849	1.3270
	min_Dist_sc	-0.000682	0.000377	0.070430	1.0314
	minDist_SS_sc	-0.002112	0.000466	5.99e-06***	1.1103
	Obsv_SS_1k_sc	0.001609	0.000450	0.000354 ***	1.2325
	SP_wooded_sc	0.002624	0.000379	4.47e-12***	1.0360
	x_coord	0.000000	0.000000	0.004508 **	1.0910
	y_coord	0.000000	0.000000	0.004067 **	1.3551
Palmate newt ***(Lissotriton helveticus)***	Intercept	0.159700	0.295800	0.589361	-
	min_Dist_sc	-0.001181	0.000250	2.43e-06***	1.0126
	SP_water_sc	-0.000414	0.000253	0.102012	1.0242
	x_coord	0.000000	0.000000	0.316794	1.0517
	y_coord	0.000000	0.000000	0.000317 ***	1.0445
Water frog ***(Pelophylax sp.)***	Intercept	0.003750	0.000435	< 2e-16***	-
	min_Dist_sc	-0.002324	0.000446	1.87e-07 ***	1.0252
	minDist_PS_sc	-0.004586	0.000528	< 2e-16***	1.1361
	SP_wooded_sc	-0.002111	0.000939	0.0246*	2.1613
	SP_buildings_sc	-0.001938	0.000779	0.0129*	1.7921
	SP_humus_sc	-0.001143	0.000737	0.1211	1.6968

For most species, the coordinates (x_coord and y_coord) were part of the best models and in some cases their p-value were also significant. In contrast, the best model for the water frog (*Pelophylax sp.)* does not include any coordinate variables.

3.3.1. COMMON FROG (*RANA TEMPORARIA*)

Both the distance to the nearest stagnant water body, as well as the distance to the nearest common frog observations showed a highly significant negative correlation with common frog abundance. Additionally, there was a positive correlation between the number of past observations within a 1000-meter radius and current frog abundance. The results showed a significant negative correlation between the proportion of buildings and common frog abundance. Both the proportions of wooded areas and humus-rich areas were also negatively correlated with common frog abundance. Lastly, the proportion of water bodies also had a significant negative relationship with common frog abundance.



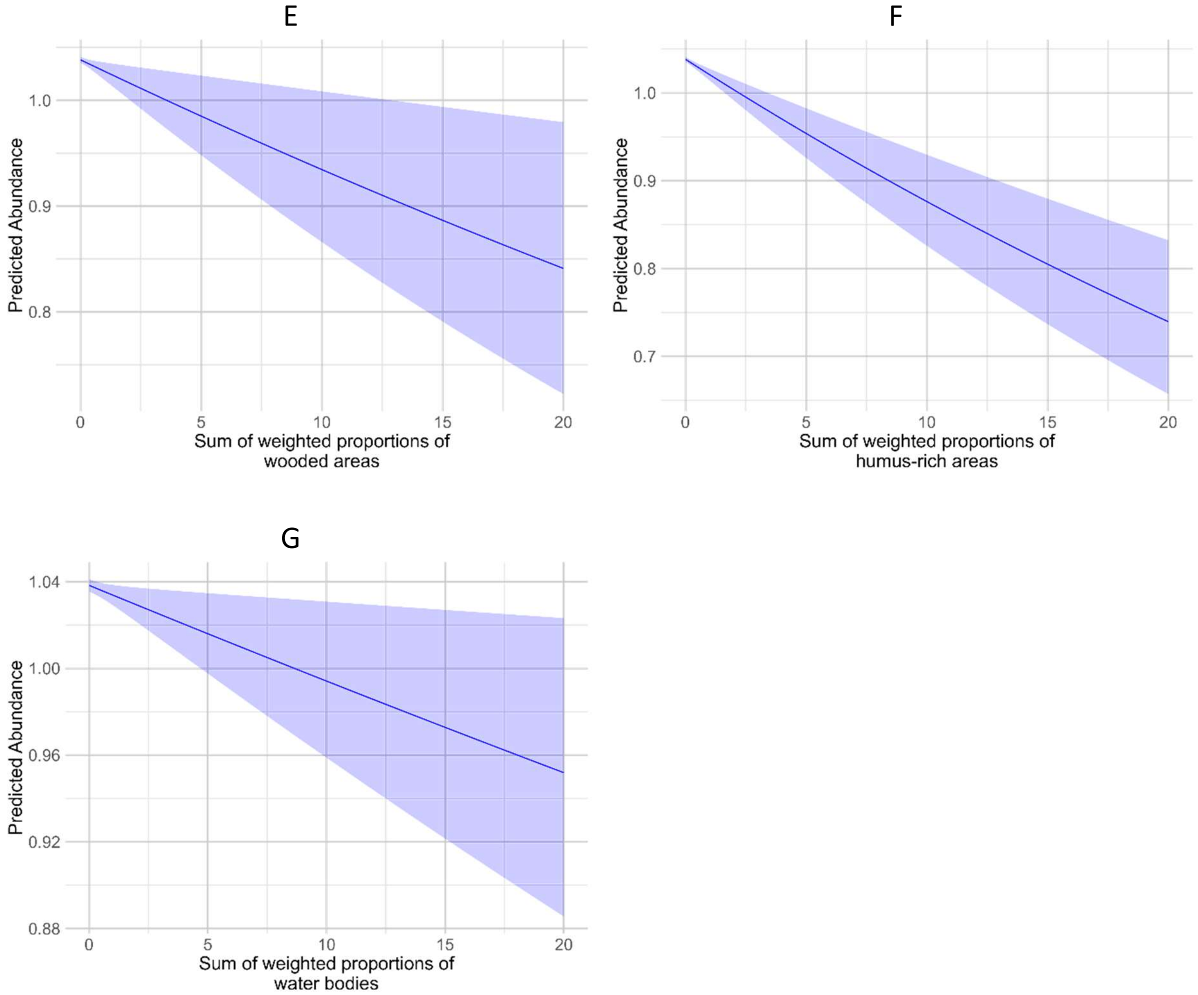


Figure 7: The effect of the distance to the nearest stagnant water body (A), the distance to the nearest past common frog observation (B), the number of past common frog observations within a 1000m radius (C), the proportion of buildings in the surrounding area (D), the proportion of wooded areas (E), the proportion of humus-rich areas (F) and the proportion of water bodies (G) on common frog abundance.

3.3.2. COMMON TOAD (*BUFO BUFO*)

Interestingly, for the common toad there was a significant negative effect of the number of stagnant water bodies within a 1000-meter radius on common toad abundance. Like the common frog, both distance variables - distance to stagnant water bodies and known common toad habitats - showed a strong negative effect on toad abundance. The number of past observations of common toads within a 1000-meter radius exhibited a very strong positive correlation. Additionally, the proportion of buildings was negatively associated with toad abundance, like the pattern observed with common frogs. Furthermore, the study found that a higher proportion of water bodies was linked to lower toad abundance.

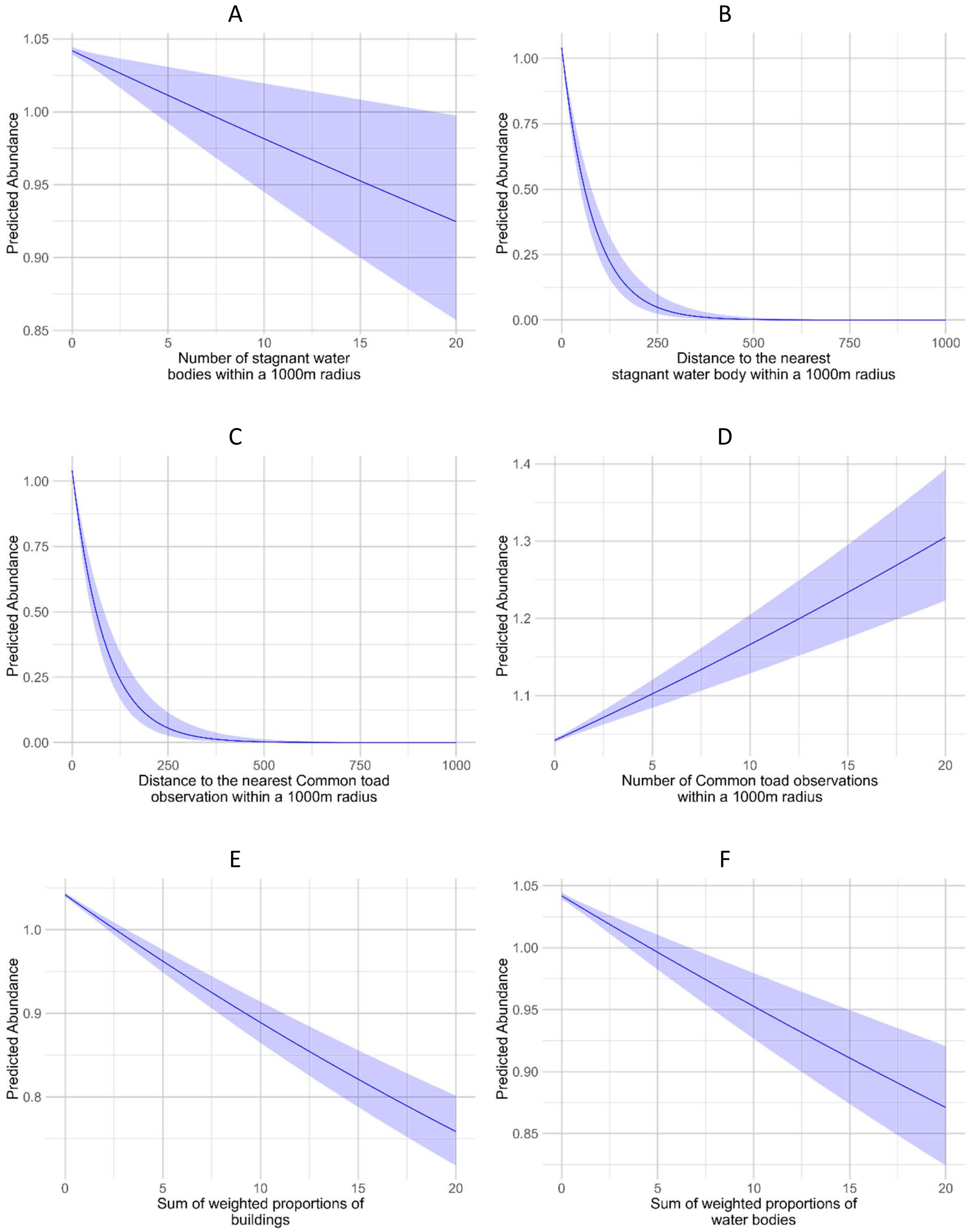
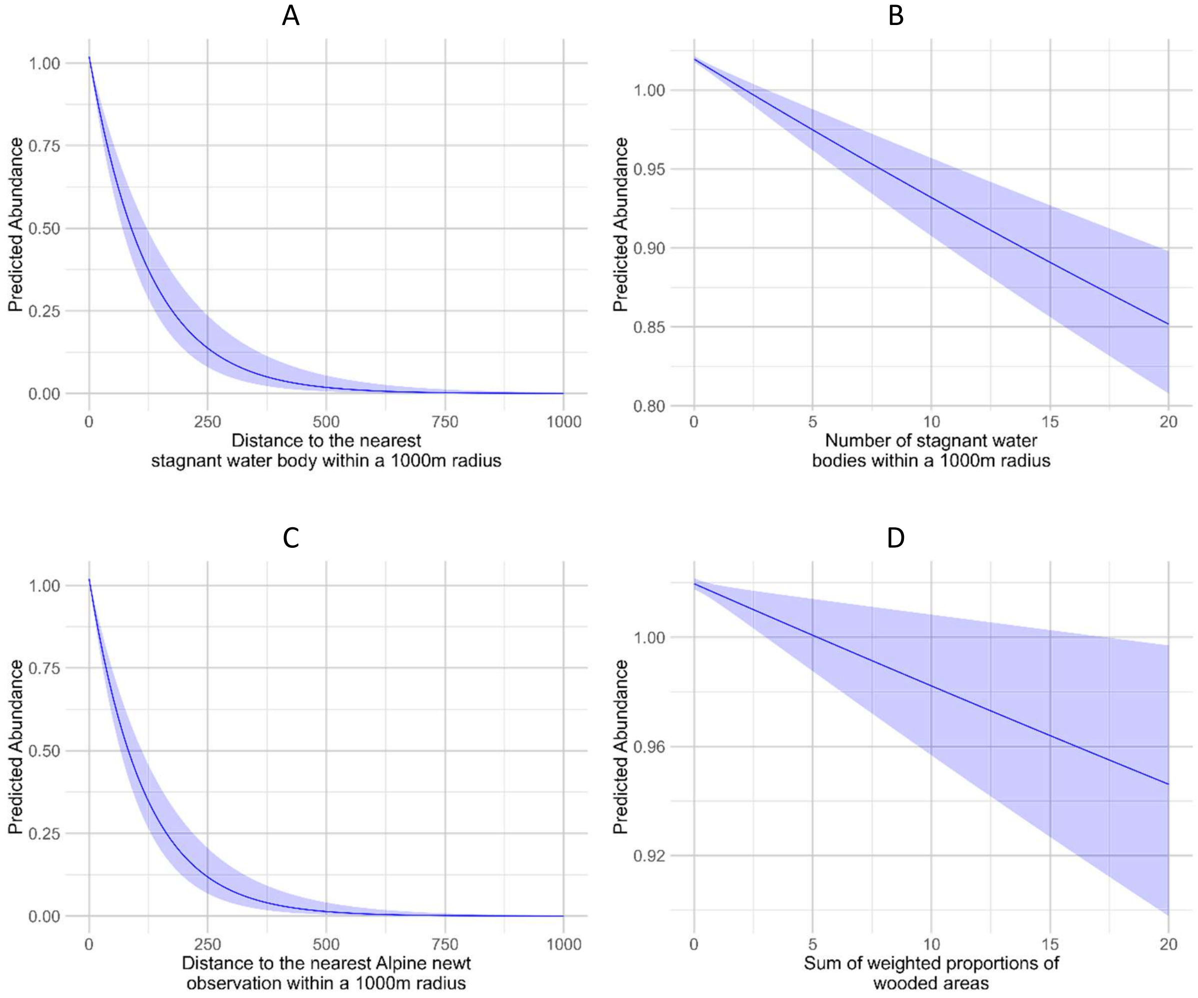


Figure 8: Predictors for the abundance of common toad in gully pots, including the number of stagnant water bodies (A), distance to the nearest stagnant water body (B), the distance to the nearest past common toad observations (C), the number of past common toad observations within a 1000m radius (D), the proportion of buildings (E) and proportion of water bodies (F).

3.3.3. ALPINE NEWT (*ICHTHYOSAURA ALPESTRIS*)

The best model for the alpine newt indicates a significant negative correlation between abundance and distance from these water bodies. The number of stagnant water bodies within a 1000-meter radius has a significant negative effect on alpine newt abundance. The distance to the nearest alpine newt observation also showed a significant negative correlation with its abundance, consistent with patterns observed across other species. The proportion of wooded areas also has a significant negative effect. Furthermore, the proportion of buildings negatively impacts alpine newt abundance, in line with trends observed for other species.



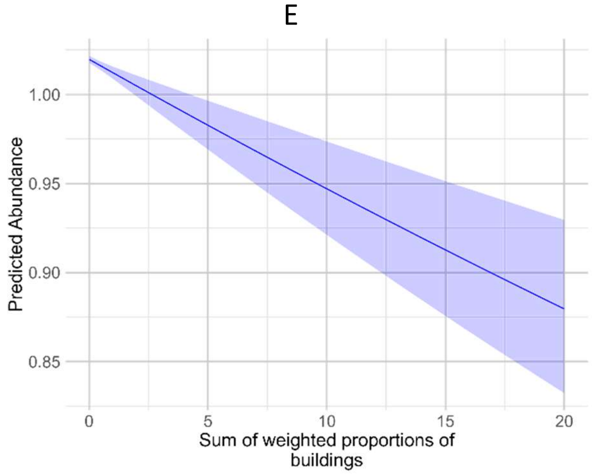
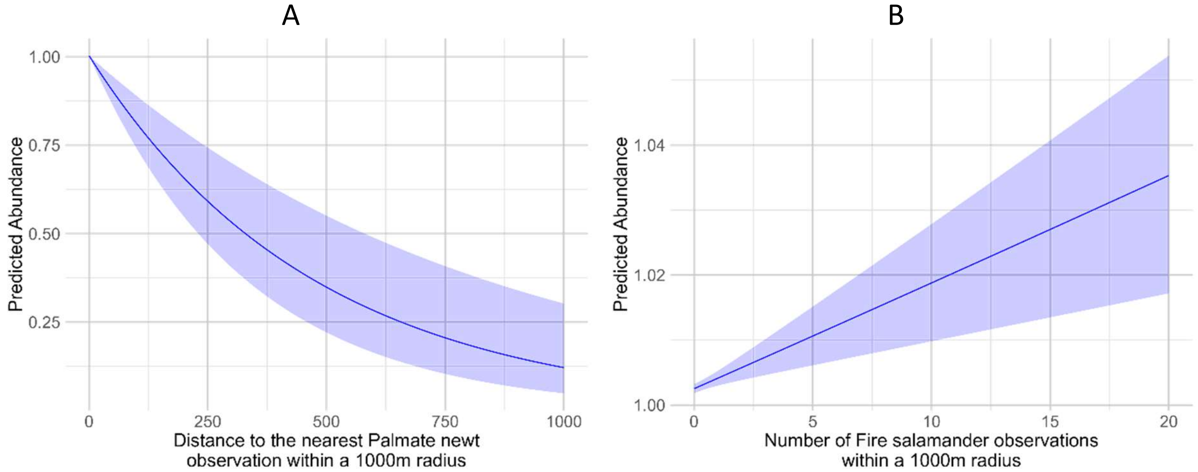


FIGURE 9: FACTORS THAT HAD AN EFFECT ON ALPINE NEWT ABUNDANCE WERE THE DISTANCE TO WATER BODIES (A), THE NUMBER OF STAGNANT WATER BODIES WITHIN A 1000M RADIUS (B), THE DISTANCE TO PAST OBSERVATIONS (C), THE PROPORTION OF WOODED AREAS (D) AND THE PROPORTION OF BUILDINGS (E).

3.3.4. FIRE SALAMANDER (*SALAMANDRA SALAMANDRA*)

The best model for the fire salamander showed that the proximity and the number of past observations within a 1000-meter radius both positively influence its abundance in the observed gully pots. The proportion of wooded areas is a significant positive predictor of abundance, highlighting the species' strong preference for forested environments. The distance to stagnant water bodies as well as the number of water bodies within a 1000-meter radius did not show significant effects in the best model.



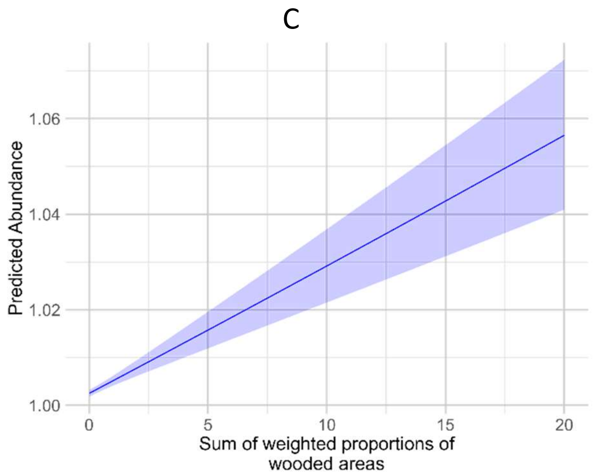


Figure 10: The effect of distance to past fire salamander observations (A), the number of past Fire salamander observations (B) and the proportion of wooded areas (C) on the abundance of the Fire salamander.

3.3.5. PALMATE NEWT (LISSOTRITON HELVETICUS)

The analysis for the palmate newt revealed only single factors significantly affecting its abundance. The model shows that the shortest distance to the nearest stagnant water body has a highly significant negative effect. This indicates that as the distance to stagnant water decreases, the abundance of palmate newts increases. In contrast, the proportion of water bodies in the area does not have a significant effect on palmate newt abundance.

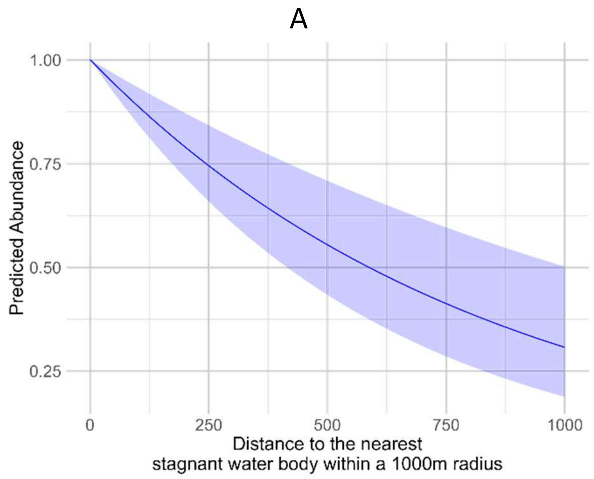


Figure 11: The proximity to water bodies (A) was the only factor significantly affecting Palmate newt abundance.

3.3.6. WATER FROG (*PELOPHYLAX SP.)*

The best ranked model describing water frog abundance demonstrated a significant negative relationship with the distance to stagnant water bodies, similar to the palmate newt. Similarly, the shortest distance to the nearest water frog observation also demonstrated a highly significant negative effect. Additionally, the proportion of wooded areas and the proportion of buildings both showed a significant negative relationship with water frog abundance. The proportion of humus-rich areas had a negative but not significant effect on water frog abundance.

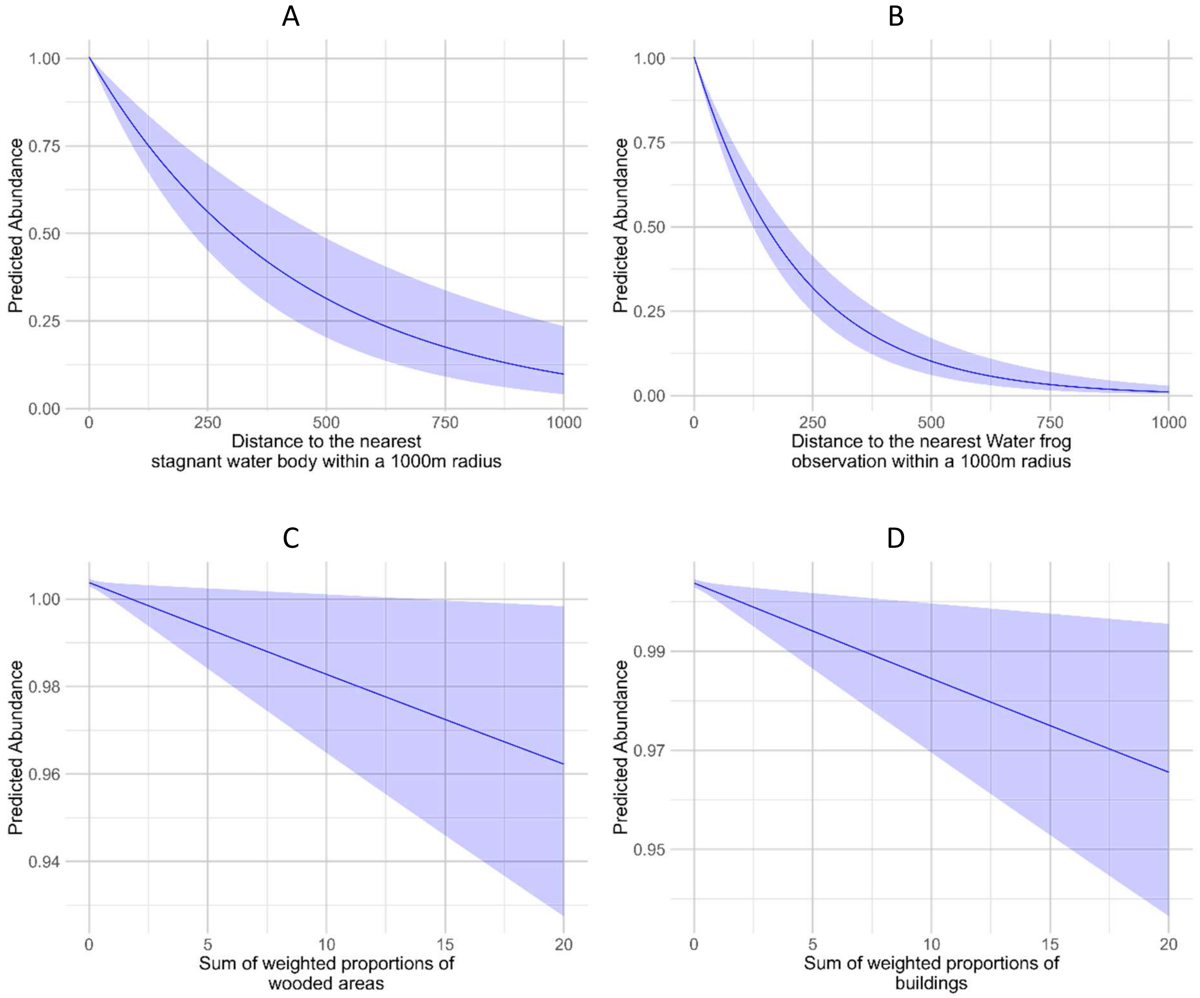


FIGURE 12: FACTORS INFLUENCING WATER FROG ABUNDANCE IN GULLY POTS, INCLUDING THE EFFECTS OF WATER BODY PROXIMITY (A), PROXIMITY TO WATER FROG OBSERVATIONS (B), THE PROPORTION OF WOODED AREAS (C), AND THE PROPORTION OF BUILDINGS (D).

Summed up, a significant commonality seems to be the negative relationship between the distance to the nearest stagnant water body and the abundance of species in gully pots. This finding suggests that proximity to water bodies is a decisive factor for conservation measures. Additionally, most species exhibit a positive association with the number of past observations within a 1000 m radius, indicating that areas with higher amphibian activity are more likely to host these species in gully pots. Conversely, the presence of buildings negatively impacts the likelihood of amphibians being found in gully pots.

4. DISCUSSION

This study aimed at improving conservation action by finding environmental factors influencing the abundance of amphibians in gully pots using species distribution modeling. By applying GIS-based methods, the results can be used to identify gully pots that represent potential amphibian traps. The analyses were conducted on abundance data collected over several years by Grün Stadt Zürich (GSZ). GIS-methods were used to rebuild study areas and determine environmental variables such as land cover, distance to water bodies and past amphibian sightings. Linear models were then used to identify the variables that best explain amphibian abundance in these urban drainage systems.

The main findings of this study include a weak spatial autocorrelation of amphibian abundance data, a strong influence of distance to water bodies and past observations as well as the negative impacts of urbanization features such as buildings.

4.1. SPATIAL AUTOCORRELATION

The calculated Moran's Indexes indicated a weak spatial correlation in the abundance data. The Moran's I correlograms, which show Moran's I values as a function of distance, showed that spatial correlation was higher at short distances but rapidly decreased. This means there is a high likelihood of finding the same amphibian species in neighboring gully pots. This also suggests that, from a conservation perspective, it would be more effective to consider measures for entire street sections rather than for single gully pots.

Spatial correlation in our data was weak but it was present. Spatial correlation represents a major problem in spatial distribution modeling (Lichstein, Simons et al. 2002, Diniz-Filho, Bini et al. 2003, F. Dormann, M. McPherson et al. 2007). When the assumption of spatial independence is compromised, Legendre (1993) suggested including a spatial structure into statistical modeling. Therefore, I used the x- and y-coordinates of the sightings as additional variables in our dredge-models to possibly enhance their explanatory power.

In studies using spatial data, it is essential to address spatial autocorrelation and apply appropriate methods to mitigate its effects. In the literature, there are several discussions on how to address spatial autocorrelation in linear models. In their review paper on how to account for spatial autocorrelation, F. Dormann, M. McPherson et al. (2007) suggest multiple methods, like adding spatial covariates into the model, the use of simultaneous autoregressive models (SAR) or conditional autoregressive models (SAR) or implement spatial generalized linear mixed models (GLMM). Kriging, as another method, allow calculating spatially correlated random effects, which can be incorporated into GLM (Diggle, Tawn et al. 1998). Finally, spatial filtering techniques remove spatial autocorrelation from the dependent variable or residuals by creating spatial filters (Griffith and Chun 2014). Each method has its strengths, depending on the characteristics of the spatial data and the goal of the analysis, and the computational resources available.

4.2. FACTORS AFFECTING ABUNDANCE IN GULLY POTS

The distance to the nearest stagnant water body had a significant negative effect on the abundance of several amphibian species in gully pots, highlighting the importance of proximity to water for these species. For the common frog and the common toad, this variable was significantly correlated to abundance, underlining the necessity of nearby aquatic habitats (Herrmann, Babbitt et al. 2005, Johansson, Primmer et al. 2005). The alpine newt and the palmate newt also showed a significant negative correlation, showing the importance of accessibility to aquatic habitats (Joly, Miaud et al. 2001). For the water frog (*Pelophylax* sp.), a significant negative relationship was found as well. Both newt species and water frogs have a limited range of activity and are highly dependent on the proximity to water bodies and the connectivity between them (Pellet and Schmidt 2005, Meyer, Zumbach et al. 2009, Céréghino, Boix et al. 2014). The best model for the fire salamander included a negative relationship with the distance to the nearest stagnant water body as well. The relationship was not significant suggesting that fire salamanders may not be as reliant on water proximity compared to other amphibian species. Indeed, the fire salamander is one of the few native amphibian species that use small streams in forests rather than stagnant water bodies for reproduction (Meyer, Zumbach et al. 2009).

Interestingly, the best models for the common toad, the alpine newt and the fire salamander showed a negative relationship with the number of stagnant water bodies in the surrounding. This result indicate that numerous water bodies might show low ecological quality, contain predators like fish or the species may prefer other types of aquatic habitats.

The proportion of water bodies in the surrounding area of the gully pots had varied effects on different species. For the common frog, this variable had a small but still significant negative effect. For the common toad, the proportion of water bodies was also negatively correlated with their abundance. The palmate newt showed a negative, but not significant relationship with the proportion of water bodies in the surrounding. This finding may indicate these species not have a strong preference for habitats dominated by extensive water bodies, but rather may thrive in environments with a different or more complex habitat structure (Pellet and Schmidt 2005, Meyer, Zumbach et al. 2009, Céréghino, Boix et al. 2014).

The number of past observations within a 1000 m radius was a significant positive predictor for multiple species, indicating that gully pots near to or within areas with a higher density of past sightings are more likely to contain trapped amphibians. Additionally, the distance to the nearest past observation played an important role. This was evident for the abundance of the common frog, common toad, alpine newt, water frog, and fire salamander, all of which showed a correlation with either the number of or the distance to past sightings. These findings underline the importance of historical activity in predicting current amphibian locations (Pellet and Schmidt 2005).

The proportion of buildings showed a significant negative correlation with the abundance of several amphibian species. For the common frog and the common toad, a higher proportion of building in the surrounding negatively impacted their abundance in gully pots. The best alpine newt and water frog models also predicted their abundance to be lower in areas with more buildings. These results align with the results of many studies which emphasize the negative effect of urbanized areas on the presence and abundance of amphibians (Knutson, Sauer et al. 1999, Gardner, Fitzherbert et al. 2007, Scheffers and Paszkowski 2012).

The proportion of wooded areas had significant effects on the abundance of fire salamanders. This result indicates a strong preference for forested environments and aligns with the fact that adult fire salamanders are exclusively terrestrial creatures, inhabiting moist deciduous and mixed forests (Meyer, Zumbach et al. 2009, Bolte, Goudarzi et al. 2023). Conversely, for the water frog, the common frog and the alpine newt, there was a significant negative relationship with the proportion of wooded areas, implying a preference for more open environments (Denoël, Duret et al. 2022). Interestingly, there was no significant correlation between the abundance of the palmate newt and the proportion of wooded areas, despite of this species being often found in wooded habitats (Meyer, Zumbach et al. 2009).

The proportion of humus-rich areas had a negative impact on both the common frog and the water frog, though the effect was not significant for the latter. Within the category of humus-rich surfaces, no distinction is made between intensively managed areas and extensively managed areas. It is quite possible that the humus-rich areas in the study perimeter were predominantly intensively managed. This could explain the negative correlation with the presence and abundance of the common frog.

4.3. LIMITATIONS AND UNCERTAINITY

There are several sources of uncertainty associated with linear regression analyses. When applying linear regression models, we assume linear relationships and the errors having consistent variance (homoscedasticity). But ecological data often show complex spatial patterns and the mentioned assumptions are not always met which can lead to biases (Zurell, Franklin et al. 2020). Another factor possibly affecting reliability of estimates is multicollinearity. Multicollinearity is present, when there is a strong relationship between multiple predictor variables. When two or more variables are highly correlated, it becomes challenging to recognize the individual impact of each predictor, as they “overlap” in their effects (Zurell, Franklin et al. 2020). In this study, Generalized Variance Inflation Factors (GVIFs) were used to analyze multicollinearity. Finally, another limitation of the study is the incompleteness of presence data, as absence data was not available for all gully pots and had to be computed. Additionally, unconsidered variables like some smaller landscape elements (e.g. hedges, wooden or stone structures), which might have influenced abundance as well, were not included in the land use data.

5. CONCLUSION AND FURTHER WORK

In this study, we observed different environmental variables having different effects on the abundance of amphibians in gully pots. The distance to water bodies generally has a positive effect on amphibian abundance, while the proportion of buildings in the surrounding and excessive humus-rich (predominantly intensively managed) areas tend to have negative impacts. Wooded areas have positive effects for some species, while others seem to prefer open habitats. Finally, past observations in the area are important for predicting amphibian abundance in gully pots.

The findings of this study may offer valuable insights for planning and prioritizing conservation measures, such as installing amphibian ladders. Using GIS-based approaches, these results could help predict potential traps within the drainage system by utilizing data on land cover and the coordinates of the gully pots (Appendix 8). Generally, gully pots near water bodies and in historically significant amphibian habitats should be prioritized for the installation of amphibian ladders. Gully pots in urban areas pose a lower risk to amphibians. However, each species has its own environmental requirements, so the potential traps in the drainage system would need to be reassessed for each species. Furthermore, it might be more effective to implement measures for entire streets rather than individual gully pots, as the likelihood of finding the same species in neighboring gully pots is high.

Prioritization is even more important, as, according to the guidelines of info fauna karch (Koordinationsstelle für Amphibien- und Reptilienschutz in der Schweiz), the amphibian ladders should be maintained at least once a year. Maintaining these ladders incurs costs, and a dirty or displaced ladder no longer achieves the desired effect.

In a continuation of this work, it would be interesting to see whether small structures like stone piles or hedges would have a significant effect on amphibian abundance, as they are important components of the landscape for amphibians. Additionally, in the selection of variables for future studies, it is important to consider that flowing water bodies are significant for species such as the fire salamander. Looking back, I should have differentiated between “standing” and “flowing” water bodies rather than using one variable for both. This would better reflect the habitat requirements of different amphibian species.

Applying the methodology to other urban areas is also crucial, as the transferability of distribution models is a discussed topic in the literature (Zanini, Pellet et al. 2009). Moreover, it is essential to address spatial autocorrelations more effectively and apply appropriate methods to mitigate their effects.

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7. APPENDIX

APPENDIX 1: TYPES OF GROUND COVER ACCORDING TO THE SWISS FEDERAL MODEL DM01

Ground cover type	**Subtypes**
Building	-
Sealed surface	Road Path Sidewalk Traffic island Railway Airport Artificial pond Other sealed surfaces
Humus-rich surface	Arable land Meadow Pasture Intensive crop (including vines) Garden High and low marsh Other humus-rich surfaces
Water body	Standing waters (lakes, ponds) Flowing waters (rivers, streams, artificial waterways)
Wooded surface	Forest Other wooded surfaces
Vegetation-free surface	Rock Scree Sand Glacier Firn Extraction, landfill Other vegetation-free surface

APPENDIX 2: THE FIVE TOP RANKED ABUNDANCE MODELS FOR THE COMMON FROG.

Nr	Model	K	AICc	ΔAICc	ω
1	count_rt_log ~ min_Dist_sc + minDist_RT_sc + Obsv_RT_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	11	-10615.03	0.00	0.32
2	count_rt_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_RT_sc + Obsv_RT_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	12	-10613.40	1.63	0.14
3	count_rt_log ~ min_Dist_sc + minDist_RT_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	10	-10613.16	1.86	0.13
4	count_rt_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_RT_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	11	-10612.98	2.05	0.12
5	count_rt_log ~ min_Dist_sc + minDist_RT_sc + Obsv_RT_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_humus_sc + x_coord + y_coord	10	-10611.46	3.57	0.05

APPENDIX 3: THE FIVE TOP RANKED ABUNDANCE MODELS FOR THE COMMON TOAD.

Nr	Model	K	AICc	ΔAICc	ω
1	count_bb_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_BB_sc + Obsv_BB_1k_sc + SP_buildings_sc + SP_water_sc + x_coord + y_coord	10	-11339.43	0.00	0.45
2	count_bb_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_BB_sc + Obsv_BB_1k_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	11	-11338.13	1.30	0.23
3	count_bb_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_BB_sc + Obsv_BB_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + x_coord + y_coord	11	-11337.51	1.92	0.17
4	count_bb_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_BB_sc + Obsv_BB_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	12	-11336.85	2.58	0.12
5	count_bb_log ~ min_Dist_sc + minDist_BB_sc + Obsv_BB_1k_sc + SP_buildings_sc + SP_water_sc + x_coord + y_coord	9	-11331.89	7.54	0.01

APPENDIX 4: THE FIVE TOP RANKED ABUNDANCE MODELS FOR THE ALPINE NEWT.

Nr	**Model**	**K**	**AICc**	**ΔAICc**	**ω**
1	count_ta_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_IA_sc + SP_wooded_sc + SP_buildings_sc + x_coord + y_coord	9	-16385.08	0.00	0.20
2	count_ta_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_IA_sc + SP_wooded_sc + SP_buildings_sc + SP_humus_sc + x_coord + y_coord	10	-16384.49	0.59	0.15
3	count_ta_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_IA_sc + Obsv_IA_1k_sc + SP_wooded_sc + SP_buildings_sc + x_coord + y_coord	10	-16384.23	0.84	0.13
4	count_ta_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_IA_sc + Obsv_IA_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_humus_sc + x_coord + y_coord	11	-16384.08	1.00	0.12
5	count_ta_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_IA_sc + Obsv_IA_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	12	-16383.76	1.32	0.10

APPENDIX 5: THE FIVE TOP RANKED MODELS FOR THE FIRE SALAMANDER

Nr	**Model**	**K**	**AICc**	**ΔAICc**	**ω**
1	count_ss_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_SS_sc + Obsv_SS_1k_sc + SP_wooded_sc + x_coord + y_coord	9	-34190.01	0.00	0.10
2	count_ss_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_SS_sc + Obsv_SS_1k_sc + SP_wooded_sc + SP_buildings_sc + SP_humus_sc + x_coord + y_coord	11	-34189.72	0.29	0.08
3	count_ss_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_SS_sc + Obsv_SS_1k_sc + SP_wooded_sc + SP_buildings_sc + x_coord + y_coord	10	-34189.48	0.53	0.08
4	count_ss_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_SS_sc + Obsv_SS_1k_sc + SP_sealed_sc + SP_water_sc + SP_humus_sc + x_coord + y_coord	11	-34188.74	1.26	0.05
5	count_ss_log ~ Anz_Gew1k_sc + minDist_SS_sc + Obsv_SS_1k_sc + SP_wooded_sc + x_coord + y_coord	8	-34188.73	1.27	0.05

APPENDIX 6: THE FIVE TOP RANKED MODELS FOR THE PALMATE NEWT

Nr	**Model**	**K**	**AICc**	**ΔAICc**	**ω**
1	count_th_log ~ min_Dist_sc + SP_water_sc + x_coord + y_coord	6	-41014.23	0.00	0.02
2	count_th_log ~ min_Dist_sc + x_coord + y_coord	5	-41013.56	0.67	0.02
3	count_th_log ~ min_Dist_sc + Obsv_LH_1k_sc + SP_water_sc + x_coord + y_coord	7	-41013.42	0.81	0.02
4	count_th_log ~ min_Dist_sc + SP_buildings_sc + SP_water_sc + x_coord + y_coord	7	-41013.41	0.82	0.02
5	count_th_log ~ min_Dist_sc + SP_wooded_sc + SP_buildings_sc + SP_water_sc + x_coord + y_coord	8	-41013.35	0.88	0.02

APPENDIX 7: THE FIVE TOP RANKED MODELS FOR THE WATER FROG

Nr	**Model**	**K**	**AICc**	**ΔAICc**	**ω**
1	count_re_log ~ min_Dist_sc + minDist_PS_sc + SP_wooded_sc + SP_buildings_sc + SP_humus_sc	7	-31164.25	0.00	0.05
2	count_re_log ~ min_Dist_sc + minDist_PS_sc + SP_wooded_sc + SP_buildings_sc	6	-31163.85	0.40	0.04
3	count_re_log ~ min_Dist_sc + minDist_PS_sc	4	-31163.58	0.67	0.04
4	count_re_log ~ Anz_Gew1k_sc + min_Dist_sc + minDist_PS_sc	5	-31163.50	0.76	0.03
5	count_re_log ~ min_Dist_sc + minDist_PS_sc + SP_buildings_sc	5	-31163.04	1.22	0.03

APPENDIX 8: MAPS OF ENZENBÜHL CEMETERY AND ITS SURROUNDINGS SHOWING THE PREDICTED ABUNDANCE OF THE WATER FROG AND THE FIRE SALAMANDER, WITH ABUNDANCE PREDICTIONS BASED ON THE BEST MODEL FOR EACH SPECIES.

Fire salamander

Water frog