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OPTIMIZING FROG SURVEYS THROUGH OCCUPANCY MODELING: AN OVERVIEW OF ENVIRONMENTAL AND METHODOLOGICAL DETERMINANTS OF ANURAN DETECTABILITY

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Abstract: Detecting the presence of a particular species in the environment is essential in studies aiming to assess the abundance and distribution of the species. Identifying the factors that affect the rate of species detectability is useful in designing monitoring programs and can lead to a more consistent study method. Here, we reviewed a set of factors that potentially influence the detection of frogs. We conducted an extensive literature review to identify key elements that affect frog detectability. Primarily, we focused on the environmental variables affecting frog species, with a brief consideration of the methodological aspects related to frog detection. We synthesized commonly used environmental and habitat variables, revealing recurring patterns and their connections with frog detectability. Additionally, we explored the methodological factors influencing frog detection and identified gaps in the current literature, proposing potential future research directions. Our findings highlight the significance of environmental factors such as temperature, precipitation, humidity, cloudiness, moon phase, and some habitat characteristics on frog detectability. Geographic biases in detectability studies limit our understanding, and expanding research into underexplored regions is crucial from a global perspective. In addition, incorporating specific environmental variables tailored to each species and habitat can enhance detection accuracy, improving our understanding of frog ecology and conservation. This review highlights the importance of accounting for detectability when surveying frogs and the need to consider all the factors influencing detectability.

Keywords: amphibians; detection probability; environmental variables; occupancy models.

INTRODUCTION

The detection of species presence is fundamental for studies on occurrence, diversity, distribution, and long-term monitoring (MacKenzie 2005; Mazerolle et al. 2007). However, species may remain undetected due to imperfect detectability, which varies across space, time, and species (MacKenzie et al. 2002; Thompson 2002), meaning that non-detection does not imply absence (MacKenzie et al. 2002). This variation can bias estimates of species richness, abundance, and distribution, leading to misinterpretation (Archaux et al. 2012). Addressing imperfect detection is therefore critical in ecological studies. Common methods for estimating detectability include mark-recapture (Otis et al. 1978), distance sampling (Buckland et al. 1993), and occupancy modeling (MacKenzie et al. 2002). Occupancy modeling is particularly common for amphibians, as it accounts for both environmental factors and the probability of species occupancy and detection (MacKenzie et al. 2002). This approach involves multiple site visits to record species presence or absence, and the construction of models based on detection histories (MacKenzie et al. 2002).

Frog species detection is challenging because of life history traits such as arboreal, leaf-litter, or fossorial habits (Duellman & Trueb 1986) and species-specific climatic responses (Ospina et al. 2013). Detection can be influenced by air temperature (Strain et al. 2016; Rivera & Folt 2018), humidity (Olson et al. 2011; Pereira-Ribeiro et al. 2019), precipitation (Rivera & Folt 2018; Asad et al. 2020), habitat structure (Curtis & Paton 2010; Moreira et al. 2015), and methodological factors (Farmer et al. 2009; Smith et al. 2014; Barata et al. 2017; Pereira-Ribeiro et al. 2017). In recent years, there has been an increase in studies aimed at estimating the detectability of anurans (e.g., Harings & Boeing 2014, Ngo et al. 2020; Flyn et al. 2023, Pereira-Ribeiro et al. 2023). However, there remains a lack of standardization in the variables and scales used, even when addressing similar processes. For example, precipitation metrics such as rainfall during sampling or cumulative daily and monthly precipitation are commonly used but inconsistently applied. Identifying factors closely associated with the high detectability of anuran species can significantly enhance monitoring programs by promoting more consistent study designs. Moreover, understanding how to measure and integrate these variables effectively into analyses is crucial for improving monitoring accuracy.

We aim to enhance the understanding of frog detectability and the factors influencing this parameter. To achieve this goal, we conducted a comprehensive review of the available literature on the subject, identifying key factors, especially environmental variables, which have been reported to influence anuran detectability. Additionally, we briefly address the significance of methodological processes in anuran detection. Initially, we synthesized and described the environmental and habitat variables utilized in these studies, identified recurring patterns and examined the relationships between these factors and anuran detectability. Subsequently, we discuss methodological factors that can influence anuran detection. Finally, we identified gaps in the current literature and proposed potential directions for future research.

MATERIAL AND METHODS

We conducted a bibliographic survey of studies that examined the effects of different factors, such as environmental and habitat variables, on anuran detectability. We compiled studies that used occupancy modeling to estimate species detectability, as this method is often applied to anurans. We considered studies that used different approaches and variations of methods since they were first proposed (e.g., Dorazio & Royle 2005, Kery & Royle 2015). To this end, we carried out a systematic review of articles published between 2002, when the method was first introduced, and August 2023, using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Standard Metho (PRISMA protocol; see Moher et al. 2015). Literature sources were accessed through the ISI Web of Science (www.webofknowledge.com) and SCOPUS (www.scopus.com) databases for the search. Our search terms included: ("detectability" OR "probability of detection") AND ("anurans" OR "Anura" OR "frog*" OR "amphibian*"). We also employed the search terms (occupancy model* AND "anurans" OR "Anura" OR "frog*" OR "amphibian*") to encompass studies exploring the impact of variables on anuran detection.

To systematize our review, we established specific inclusion and exclusion criteria. We included only original studies that empirically examined factors influencing anuran detectability. We excluded studies that assumed constant detectability, i.e., those that did not consider variations in detection probability under different environmental or methodological conditions. Data extraction was performed by collecting information on the variables analyzed (e.g., temperature, humidity and wind speed) and the methodologies used in the selected studies, as presented in Table S1. Additionally, during the literature search, we reviewed the reference lists of the articles found in the databases to ensure that no relevant studies were overlooked. Our focus remained exclusively on articles assessing frog detectability, excluding those focused on other amphibians or reptiles, such as salamanders, caecilians, or lizards. In cases where both salamanders and frogs were assessed within the same study but the results were reported separately, we extracted data solely for the frog species.

RESULTS AND DISCUSSION

We obtained 192 articles in our search based on keywords and included additional articles from reference lists of papers found in the ISI Web of Science search. Among these, 56 articles (29.1%) met the criteria and were included in this review.

Frogs are a taxonomically and ecologically complex group characterized by diverse habits and reproductive modes (Haddad and Prado 2005). Their physiological and anatomical traits—such as permeable skin, limited dispersal capacity, and dependence on water quality, precipitation, and humidity for reproduction—make them particularly sensitive to environmental conditions, especially climate factors (Duellman & Trueb 1986). Consequently, frog detectability is influenced by several external factors, including climate and habitat structure. In this review, we identified 17 environmental and habitat factors that determine species detectability in the examined studies, as represented in Figure 1.

We classified these factors into two groups — environmental conditions and habitat characteristics — and discussed their relationships with species detectability below.

Influence of environmental conditions on the detectability of frogs

Air temperature

Air temperature influences anuran activity and reproduction by affecting physiological processes, behavior, and habitat conditions (Stuart et al. 2008; Gunderson & Leal 2013). Higher temperatures can increase metabolic rates (Gunderson & Leal 2013), increasing activity and detectability. Moreover, specific temperature ranges are often required for breeding initiation and completion (Duellman & Trueb 1986). Among the factors affecting frog detectability, air temperature is the most studied,

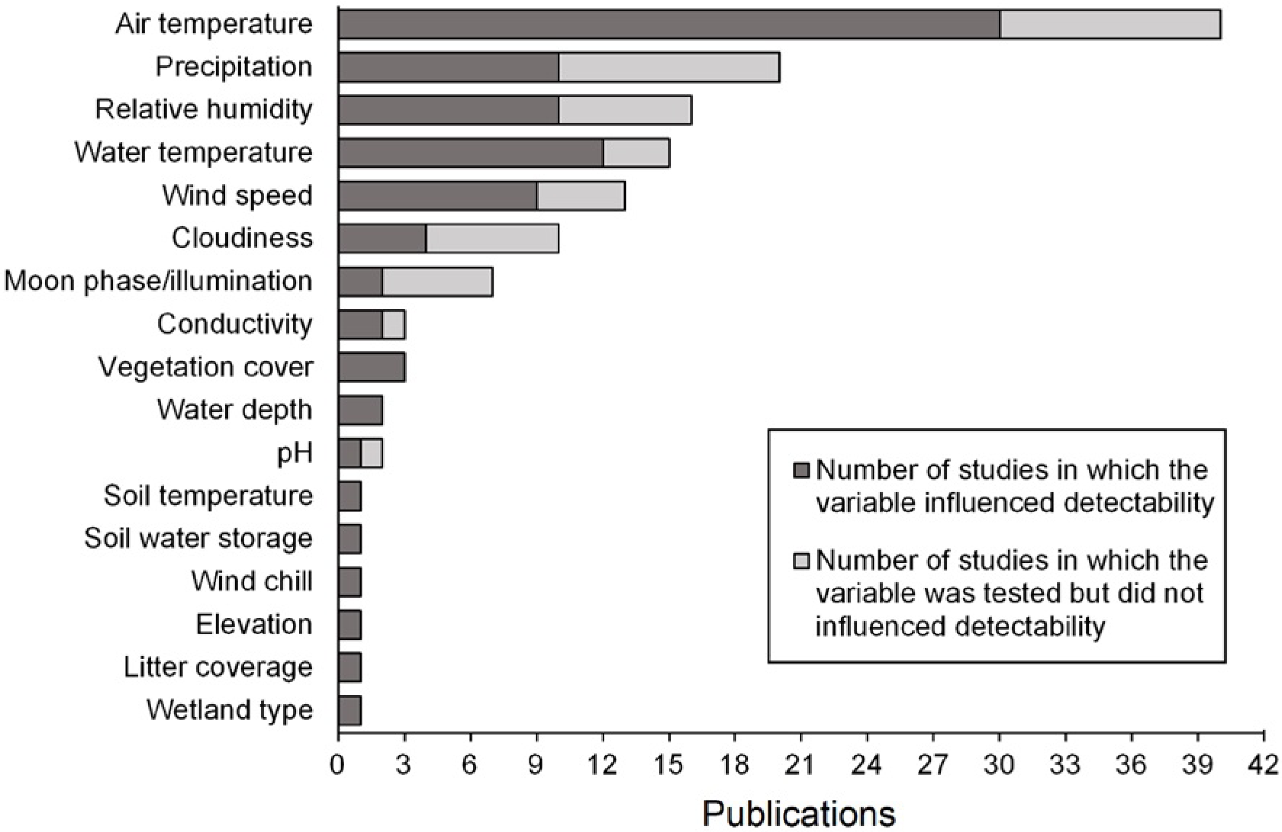

Figure 1. Environmental and habitat factors that influence the detectability of frogs in relation to the number of studies that tested these factors.

with 30 studies highlighting its impact (Fig.1, Table S2). Generally, detectability increases with increasing temperature (e.g., Cook et al. 2011, Petitot et al. 2014, Strain et al. 2016). However, responses vary by species and location (e.g., Schmidt & Pellet 2005). For example, in cold regions, species may cease activities in response to falling temperature values beyond species-specific limits (Howard 1980, Gilbert et al. 1994), reducing their detectability under colder conditions. In Michigan, for example, males of *Boreoana sylvatica* (LeConte, 1825) become active when air temperatures exceed 8 to 10 ºC (Howard 1980). Within this temperature range, the detectability of this species remains between 30% and 40%, exponentially increasing with increasing air temperature, reaching a 90% probability of detection at temperatures between 30 to 32 ºC (Rollof et al. 2011). Conversely, in tropical regions characterized by high temperatures, species may exhibit a negative relationship between temperature and detectability, meaning that the probability of detecting the species decreases with increasing temperature. For example, in Costa Rica, air temperature had a negative influence on the detectability of four species, with a higher probability of detecting the species within the temperature range of 20 to 22 ºC, considerably decreasing detection (by approximately 50%) with increasing temperatures (Rivera & Folt 2018). Consequently, accounting for local climatic variations is paramount when interpreting the influence of air temperature on frog detectability in a particular study. In addition, it is important to note that for some species, the effect of temperature can be gradual along a gradient between negative and positive, within a range in which the effect can be expressed more sharply. For example, in Maryland, in the United States, over a temperature range of approximately -6 ºC to 37 ºC, the probability of detection of *Lithobates sphenocephalus* (Cope, 1886) increased with temperature below 10 ºC, peaked between 10 ºC and 21 ºC, but declined as temperatures rose above 26 ºC (Brander et al. 2007). Weir et al. (2005) also reported a quadratic effect of temperature on the detectability of five anuran species, indicating that the highest proportion of species detected occurred within an ideal temperature range. Thus, it is important to consider linear and non-linear relationships with the detection of the temperature in the models.

<u>Precipitation</u>

Precipitation influences anuran activity, breeding, and survival by creating or expanding breeding pools, affecting detectability throughout the year. Many species rely on rainfall to trigger breeding events (Duellman & Trueb 1986; Pough et al. 2003; Pereira-Ribeiro et al. 2020a). In Argentina, the detectability of *Melanophryniscus* aff. *montevidensis* (Philippi, 1902), a rare species with explosive reproduction, is strongly linked to short-term rainfall, especially precipitation within 24-72 hours (Friedman et al. 2016). This pattern aligns with other studies indicating the influence of short-term rainfall on anuran activity (Pereira Ribeiro et al. 2020a). However, the relationship between precipitation and detectability varies across species and regions. Positive associations have been reported in the United States (Weir et al. 2005, Johnson et al. 2016), Brazil (Ribeiro Jr et al. 2018), and Costa Rica (Rivera et al. 2018), whereas negative correlations have been reported in the U.S. (Weir et al. 2005), Canada (Murray et al. 2015), and Malaysia (Asad et al. 2020). Even the same species can respond differently to rainfall depending on environmental conditions or locations. For example, precipitation had a positive effect on the detectability of *Aquarana catesbeiana* (Shaw, 1802) in ephemeral aquatic systems in the United States (Johnson et al. 2016), whereas rainfall had a contrasting negative effect in wet Canadian regions where this species was introduced (Murray et al. 2015). These variations highlight the complexity of anuran-environment interactions and the need for context-specific ecological assessments.

<u>Water temperature</u>

Water temperature is crucial for frog survival and juvenile development and particularly influences larval growth (Moore 1939). Many anuran species lay eggs in aquatic habitats where embryos and larvae face daily temperature fluctuations (Haddad & Prado 2005). Detectability often varies with water temperature, especially during larval stages, with studies from Brazil and the United States showing positive correlations between tadpole detectability and water temperature, depth, and electrical conductivity (Curtis & Paton 2010; Moreira et al. 2015, 2016).

It is important to note that water temperature can also influence the detectability of adult frogs. For example, research in the United States revealed that the detectability of seven anuran species was positively influenced by water temperature, indicating that these frogs were more likely to engage in calling activity during warmer nights (Cook et al. 2011). Similarly, in Brazil, a study reported that water temperature was positively correlated with the detectability of a stream-dwelling species, with higher detection rates with increasing water temperature (Pereira-Ribeiro et al. 2023). This information holds significant importance as it aids researchers in planning and conducting more effective long-term monitoring programs, considering the dynamic influence of water temperature on anuran detectability throughout different life stages.

Relative air humidity

As anurans are quite susceptible to desiccation, high levels of humidity are a requirement and a determining factor for the presence of species with specific reproductive modes (see Da Silva et al. 2012). The importance of air humidity in the detection of anurans has been shown in several studies at the community level (Strain et al. 2016, Pereira-Ribeiro et al. 2019) or at species level (e.g., Olson et al. 2011, Monroe et al. 2017, Asad et al. 2020, Green et al. 2020, Pereira-Ribeiro et al. 2020b). Air humidity can be especially important in the detectability of direct-development anuran species that reproduce on the forest floor, such as species of Brachycephaloidea, since they depend on rain and/or high air humidity rather than aquatic habitats (Duellman & Trueb 1986, Donnelly & Crump 1998, Haddad & Prado 2005). A study on the occupancy and abundance of *Eleutherodactylus* frogs in Puerto Rico showed that the probability of *E. wightmanae* (Schmidt, 1920) detection was positively related to the relative humidity of the local environment (Monroe et al. 2017). Similarly, in Hawaii, where two species of *Eleutherodactylus* were introduced, air humidity positively influenced the detectability of *E. coqui* (Thomas, 1966) (Olson et al. 2011). Despite this, there are relatively few studies that have assessed the detectability of communities or species living in the leaf litter of forests (Olson et al. 2011, Monroe et al. 2017, Vera Alvarez et al. 2019).

Wind speed

Wind can reduce frog detectability, as many anurans limit activity during high wind speeds to avoid desiccation and calling interference (Henzi et al. 1995; Dorcas & Foltz 1991; Oseen & Wassersug 2002; Steelman & Dorcas 2010). Strong winds have been linked to lower detection rates in various species, such as *Litoria burrowsae* (Scott, 1942) in Tasmania and *Eleutherodactylus coqui* in Hawaii, which is likely due to calling cessation and increased desiccation risk (Olson et al. 2011; Cashins et al. 2015). However, the effect of wind on frog detectability may differ between species in the same location (Weir et al. 2005 Strain et al. 2016). One study revealed that the detection probability of three frog *Dryophytes chrysoscelis* (Cope, 1880), *D. versicolor* (LeConte, 1825), and *Pseudacris crucifer* (Wied-Neuwied, 1838) decreased as the wind speed increased, whereas the detection of another trio of frog species, *Anaxyrus americanus* (Holbrook, 1836), *Aquarana clamitans* (Latreille, 1801), and *Boreorana sylvatica* (LeConte, 1825) exhibited an inverse trend, increasing with increasing wind speed (Strain et al. 2016). Researchers have hypothesized that the increased detection of the latter three species under windy conditions might be attributed to the reduced calling activity of sympatric species. Consequently, this could increase the ability of observers to detect *Anaxyrus americanus*, *Aquarana clamitans*, and *Boreorana sylvatica* (Strain et al. 2016).

Cloudiness

Cloudiness can affect important ecological processes that determine the distributions of plants and animals, influencing various aspects, from animal behavior to survival, and crucial habitat factors, such as sunlight, rainfall, surface temperature, and leaf wetness (Wilson & Jetz 2016).

Cloudiness can have variable effects on amphibian detectability, with both positive and negative relationships observed in different studies. Positive relationships have been reported for *Dryophytes chrysoscelis*, *Pseudacris crucifer* (Wied-Neuwied, 1838), and *Eleutherodactylus planirostris* (Cope, 1862) in the U.S. (Weir et al. 2005; Olson et al. 2011; Strain et al. 2016), whereas negative associations have been reported for *Anaxyrus americanus* and *Dryophytes versicolor* (Weir et al.

2005). However, most studies have reported no significant relationship between cloudiness and detectability (see Fig. 1 and Table S2).

Moon phase/illumination

Moon phase and illumination can influence frog detectability by modulating activity patterns related to predator avoidance, foraging, and reproductive behaviors, such as calling (Grant et al. 2012). However, of the nine studies examining these variables, only two identified significant associations. In the U.S., moon illumination explained the variation in detection of six out of the ten species studied (Weir et al. 2005). Similarly, in Malaysia, higher lunar phases increased detectability in *Leptobrachella parva* Dring, 1983, *Alcalus baluensis* Boulenger, 1896), *Limnonectes* cf. *kuhlii* (Tschudi, 1838), and *Leptobrachium abbotti* (Cochran, 1926), whereas *Hylarana* cf. *raniceps* (Peters, 1871) and *Limnonectes leporinus* (Andersson, 1923) showed negative associations (Asad et al. 2020).

Influence of habitat conditions on the detectability of frogs

Habitat composition is a key factor in structuring frog communities, as a high availability of microhabitats provides a wider range of microclimates, allowing for the specialization of multiple reproductive modes (Haddad & Prado 2005). While studies on the influence of habitat characteristics on frog detectability are less common than those on environmental conditions, several investigations have explored this aspect. These studies have revealed both positive and negative correlations between the detectability of both adult frogs and larvae and various water characteristics, such as conductivity (Klaver et al. 2013, Moreira et al. 2016), pH (Pereira-Ribeiro et al. 2023), water depth (Curtis & Paton 2010, Moreira et al. 2016), and wetland characteristics (Hansen et al. 2012, Hossack et al. 2015). Additionally, research has identified links between the probability of detecting frog species and soil characteristics, including temperature (Tanadini & Schmidt 2011) and water storage (Friedman et al. 2016). Vegetation and leaf litter covering forest ground have also been examined in studies conducted in Brazil (Flynn et al. 2023, Moreira et al. 2015, 2016) and the United States (Curtis & Paton 2010, Hossack et al. 2015). Furthermore, elevation has demonstrated an impact on frog species detectability in Puerto Rico, where researchers suggested that this variable serves as a valuable proxy for modeling the influence of other elevation-related environmental factors, such as humidity and temperature, on detection probabilities (Campos-Cerqueira & Aide 2017). Environmental conditions are more commonly investigated to assess frog detectability than habitat characteristics because they tend to exhibit considerable variation across sampling occasions (Mackenzie et al. 2002). Additionally, the influence of habitat characteristics on detectability can vary substantially depending on the life history of each species, leading to diverse effects among different species. Recognizing the significance of both environmental conditions and habitat characteristics in shaping frog detectability is crucial for comprehensive ecological understanding and effective conservation efforts.

Influence of methodological processes on the detectability of frogs

Monitoring is vital for evaluating conservation efforts, policies, and resource allocation (Lindenmayer & Likens 2010). Frogs are commonly monitored through auditory surveys due to their detectability, although the effectiveness of these programs can vary based on sampling protocols, affecting accuracy (Crouch & Paton 2002). Detection probabilities differ among species and methods, emphasizing the need for standardized sampling techniques (Gooch et al. 2006, Petitot et al. 2014, Wassens et al. 2017).

The auditory search method is widely used in monitoring programs to assess the distribution and abundance of anurans (Crouch & Paton 2002). While it provides valuable data on amphibian population trends (Mossman et al. 1998), it may not detect all species. For example, in France, it was not sufficiently effective to ensure 95% detection certainty for three species, although it was effective for others (Petitot et al. 2014). The duration of auditory searches also influences detection. Gooch et al. (2006) reported that 10-minute searches detected more species than 3-minute searches did, but 94% of species were detected within the first 5 minutes, suggesting varying effectiveness depending on species characteristics.

Sampling methods can also influence anuran species detectability, depending on the group or life stage. For example, the use of PVC pipes as a capture method has been shown to improve detectability for certain species (Farmer et al. 2009, Pereira-Ribeiro et al. 2017, Hutton et al. 2024). Additionally, tools such as dipnets and frog loggers have proven effective. In a private reserve in the United States, dipnet surveys achieved high detection probabilities for *Pseudacris* species and *Anaxyrus terrestris*. Frog loggers, in particular, had the highest detection probabilities for five anuran species compared to other methods (Farmer et al. 2009). When focusing on the larval stage of anurans, studies indicate that funnel traps, dipnets, and fyke nets can positively influence the detectability of tadpoles from several species (Farmer et al. 2009, Wassens et al. 2017). Observer experience also affects detection rates, with less experienced observers potentially introducing bias or requiring more visits to compensate for lower detection rates (Weir et al. 2005, Smith et al. 2014, Barata et al. 2017; Royle & Link 2006, Miller et al. 2001).

Therefore, monitoring programs should carefully select research methods and consider factors influencing detection rates. Choosing the most suitable field method for the species and objectives is crucial to enhance efficiency (Wassens et al. 2017). Ideally, using a combination of methods can improve detectability and occupancy estimates for multiple species.

Gaps within the literature

Geographic variation

Approximately 62% of the studies were conducted in North America and Europe, highlighting a geographic bias common in ecological research (Conrad et al. 2011). Notably, studies in Africa are lacking (Fig. 2), although Africa hosts over a quarter of the world's biodiversity hotspots (Myers et al. 2000), which are rich in frog species (Channing 2001; Penner et al. 2011). Additionally, studies are scarce in tropical regions, which have the highest amphibian diversity and species endemism (Frost 2024; Duellman 1988). This geographic disparity is well-documented, with research concentrated in developed regions, while many developing countries remain underexplored

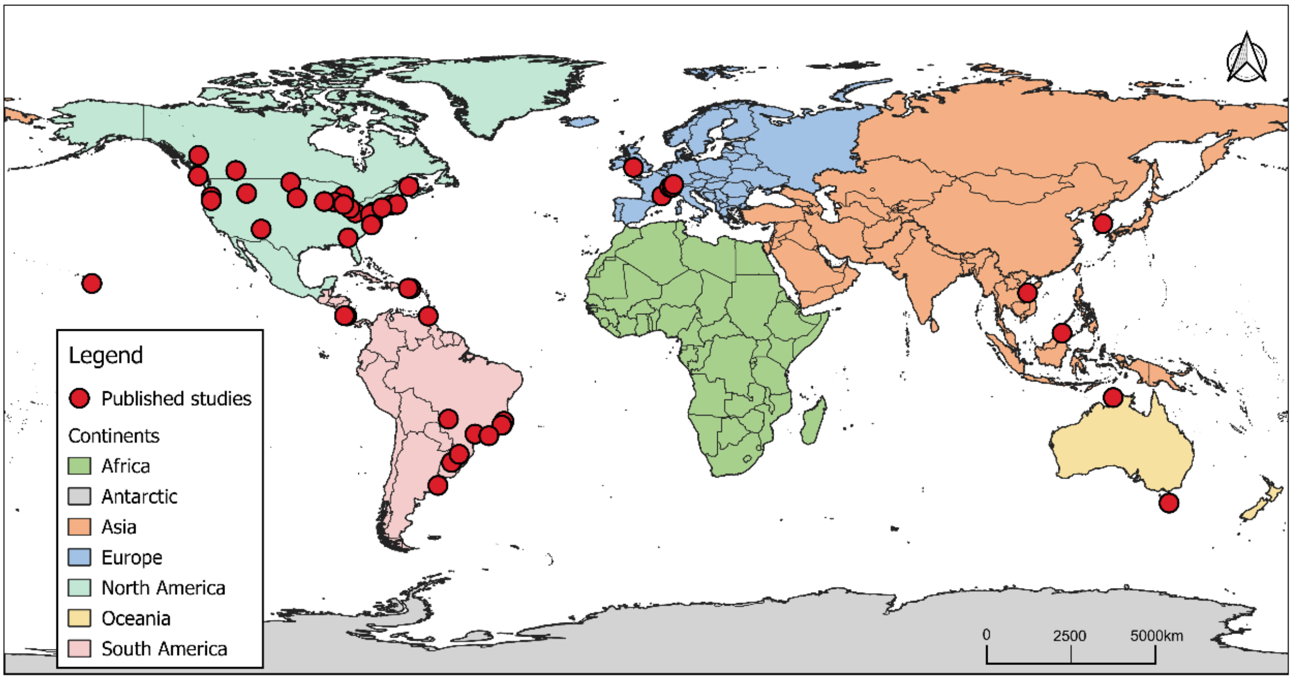

Figure 2. Spatial distribution of studies that showed the influence of environmental and habitat factors on the detectability of frogs. The published studies are indicated with red circles.

(Di Marco et al. 2017). Several factors contribute to this limited presence of studies in developing countries, including the scarcity of financial resources to support research and the challenges associated with publishing research findings in specialized journals that are often faced by scientists from these regions (see Salager-Meyer 2008).

Addressing this geographic bias necessitates the implementation of funding initiatives and incentives to encourage research in these underrepresented regions across the globe. Furthermore, given the alarming implications of climate change (see Bellard et al. 2012), there is an urgent need to intensify research endeavors focused on geographically exploring how environmental factors influence anuran detectability. This knowledge is essential for the effective planning of long-term monitoring programs that can adapt to the variation in species detection patterns in response to changing climates.

Measurement of variables

The environmental variables used in the models to assess species detection probability were measured through various methods, with most being continuous variables (Table 1). Factors such as precipitation, wind speed, and cloudiness were represented by continuous, categorical, or binary variables.

The methods for measuring factors such as precipitation varies based on study objectives or available resources. Precipitation is commonly measured in millimeters, but other approaches include daily rainfall (Roloff et al. 2011, Murray et al. 2015) or accumulated precipitation over intervals (Friedman et al. 2016, Johnson et al. 2016), with some studies using categorical or binary representations (Rivera & Folt 2018, Ngo et al. 2020). The impact of measurement type on outcomes is uncertain, and most studies use continuous variables. Categorical or binary measures may be more appropriate in areas with limited meteorological infrastructure, where alternative variables such as rainy days can be used (Johnson et al. 2016, Harings & Boeing 2014). Due to varying field and analytical methods, direct comparisons can be challenging. Researchers must carefully select and describe methods to ensure reproducibility and enable cross-study comparisons.

Variables and trait-based variation

Anurans occupy diverse habitats, including arboreal, semi-arboreal, terrestrial, fossorial, and cryptozoic environments, with a variety of reproductive modes linked to environmental factors, such as water availability and precipitation (Haddad & Prado, 2005). As noted earlier, the effects of variables on detectability can vary by species and location. However, we believe that additional environmental factors, which may significantly influence frog detectability, have been underexplored.

Some variables, such as the dew point (Smith et al. 2014) and water turbidity (Sewell et al. 2010), have been examined in studies but have shown no effect on species detectability. Other factors, particularly those relevant to specific habitats, may warrant further investigation. For species inhabiting streams, factors such as water flow, speed, quality (e.g., pH, dissolved oxygen, pollutants), and nutrient levels may influence detectability due to their effects on species activity and survival (Almeida-Gomes et al. 2014). For leaf-litter frogs, variables such as litter moisture, pH, composition, and local arthropod density could improve detectability models. Therefore, incorporating more specific, habitat-related variables is recommended to enhance our understanding of the effects of environmental influences on anuran detectability.

Species interactions influence distributions at broad spatial scales (Gaston 2003), and biotic factors strongly affect amphibian breeding site selection (Banks & Beebee 1987). These variables can impact frog occupancy and detectability, particularly with respect to predators or competitors. However, biotic factors are often overlooked in detection studies. Research has highlighted the effects of predators (Kroll et al. 2008, Klaver et al. 2013), beavers (Popescu & Gibbs 2009, Hossack et al. 2015), and co-occurring anurans (Schmidt & Pellet 2005) on occupancy. Nonetheless, the influence of these biotic factors on anuran detectability remains relatively unexplored (Hossack et al. 2015, Hamer & Horányi 2024). We believe that incorporating biotic variables into detection models, such as the presence of predators and competitors, the diversity and density of invertebrates, and the diversity of anuran species, can provide valuable insights into the broader ecological context.

Table 1. Description of the measured variables used in the models to test the effects of the environmental factors on the detectability of the species.

Variable	Type	Description	Source
Air temperature	Continuous	Minimum, average and / or maximum temperature (° C or ° F) of the occasion	MacKenzie et al. 2002, Weir et al. 2005, Schmidt & Pellet 2005, Pellet & Schmidt 2005, Mazerolle et al. 2005, Sung et al. 2006, Gooch et al. 2006, Brander et al. 2007, Sewell & Griffiths 2010, Cook et al. 2011, Roloff et al. 2011, Dostine et al. 2013, Lehtinen & Witter 2014, Harings & Boeing 2014, Smith et al 2014, Murray et al. 2015, Barrett et al. 2016, Friedman et al. 2016, Johnson et al. 2016, Gustafon & Newman 2016, Strain et al. 2016, Rivera & Folt 2018, Vera Alvarez et al. 2019, Cassel et al. 2019, Swanson et al. 2019, Asad et al. 2020, Ngo et al. 2020, Pereira-Ribeiro et al. 2020, Flynn et al. 2023.
Precipitation	Continuous / Categorical/ Binary	Continuous (mm): Daily rainfall, Accumulated precipitation 24, 48 or 72 hours before sampling, Precipitation accumulated during the time of the occasion. Categorical: none, mild, moderate, heavy, or torrential. Binary: Occasion with or without rain.	Weir et al. 2005, Roloff et al. 2011, Murray et al. 2015, Friedman et al. 2016, Johnson et al. 2016, Ribeiro Jr et al. 2018, Rivera & Folt 2018, Asad et al. 2020, Ngo et al. 2020.
Water temperature	Continuous	Minimum, average and / or maximum temperature (° C or ° F) of the occasion at each site	Gooch et al. 2006, Curtis & Paton 2010, Sewell et al. 2010, Cook et al. 2011, Dostine et al. 2013, Smith et al. 2014, Petitot et al. 2014, Moreira et al. 2015, 2016, Strain et al. 2016, Pereira-Ribeiro et al. 2020, Pereira-Ribeiro et al. 2023
Relative humidity	Continuous	Relative air humidity (in%) on the day or during the occasion	Sung et al. 2006, Olson et al. 2011, Lehtinen et al. 2016, Strain et al. 2016, Monroe et al. 2017, Pereira-Ribeiro et al. 2019, Asad et al. 2020, Green et al. 2020, Ngo et al. 2020, Pereira-Ribeiro et al. 2020Sung et al. 2006, Lehtinen et al. 2016, Monroe et al. 2017, Pereira-Ribeiro et al. 2019, Green et al. 2020, Ngo et al. 2020, Pereira-Ribeiro et al. 2020

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Variable	**Type**	**Description**	**Source**
Wind speed	Continuous / Categorical	Continuous: Average or maximum speed (km per hour). Categorical: Beaufort scale or classification code (for example, 0 = none, 1 = breeze (1–11 km/ h), 2 = light (11–21km/h), 3 =moderate (21–38 km/h), 4 = strong (> 38 km/h)	Weir et al. 2005, Popescu & Gibbs 2008, Curtis & Paton 2010, Olson et al. 2011, Tanadini & Smith 2011, Smith et al 2014, Gustafon & Newman 2016, Strain et al. 2016, Cashins et al. 2015
Cloudiness	Continuous / Categorical	Continuous: Percentage (%) of cloud cover by visual estimate. Categorical: Ascending ordinal classification code (for example, 0-clear sky, 1-few clouds, 2-partly cloudy, 3-cloudy, 4-drizzle, 5-rain, or 0 = none, 1 = 0–25%, 2 = 25–50%, 3 = 50–75%, 4 = 75–100%)	Weir et al. 2005, Olson et al. 2011, Cashins et al. 2015, Strain et al. 2016
Moon phase/ illumination	Continuous	Percentage (%) of visible lunar disc	Weir et al. 2005, Asad et al. 2020
Conductivity	Continuous	Water conductivity (in uS / cm) at each site, on each occasion	Klaver et al. 2013, Moreira et al. 2016
pH	Continuous	pH scale	Pereira-Ribeiro et al. 2023
Water depth	Continuous	Water depth (in cm) at each site, at each sampling	Curtis & Paton 2010, Moreira et al. 2016

CONCLUSIONS

Studying anuran detectability is essential for ecological research, with significant implications for the conservation, management, and understanding of amphibians. This review explored the complex relationships between frogs and environmental variables influencing their detectability across habitats and regions.

Anuran detectability varies due to species-specific behaviors, reproductive modes, and environmental responses, emphasizing the need for tailored conservation strategies, especially in the face of climate change. Factors such as temperature, precipitation, wind, moon phase, and habitat structure not only affect detectability but also influence activity patterns and reproductive success, making them key considerations in conservation planning.

The geographic bias in detectability studies, with a focus on North America, highlights the need for expanded research on biodiversity hotspots and tropical regions to better identify global patterns and trends.

Finally, incorporating species-specific variables into research models can improve detectability assessments, supporting cost-effective, long-term monitoring and more effective conservation efforts.

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SUPPLEMENTARY MATERIAL

Table S1. Types of information extracted from each study included in this review.

Table S2. Complete list of environmental and habitat factors that influence the detectability of frogs and studies that tested the respective factors.

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