CLIMATE CHANGE COULD REDUCE THE GEOGRAPHIC DISTRIBUTION OF THE NATTERJACK TOAD IN SEMI-ARID REGIONS: A 34-YEAR STUDY IN CENTRAL SPAIN

EL CAMBIO CLIMÁTICO PODRÍA REDUCIR LA DISTRIBUCIÓN GEOGRÁFICA DEL SAPO CORREDOR EN REGIONES SEMIÁRIDAS: UN ESTUDIO DE 34 AÑOS EN EL CENTRO DE ESPAÑA

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Summary

Amphibians are globally threatened due to pollution, infection diseases, invasive species, habitat loss and climate change. Rising temperatures and shifts in precipitation regimes can have a major impact on the persistence of amphibian populations, especially in semi-arid regions. In this study, we used a long term time series spanning 34 years in central Spain to evaluate the effect of three climatic variables on the reproductive success of the natterjack toad (*Epidalea calamita*) in temporary ponds.

Our results showed that reproductive success was only possible for seven years (20.6%). We found that reproductive success is positively related to the accumulated spring precipitation, while negatively related to mean spring temperature and spring evaporation. This study highlights the importance of conserving and restoring amphibian breeding habitats in order to minimize the potential impacts of climate change and habitat loss.

Keywords

Biogeography; climatic variables; Community of Madrid; conservation; *Epidalea calamita*; phenology; reproductive success; temporal series; temporary ponds; weather conditions

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Resumen

Los anfibios están amenazados globalmente debido a la contaminación, las enfermedades infecciosas emergentes, las especies invasoras, la pérdida de hábitat y el cambio climático. Un incremento de las temperaturas y cambios en los regímenes de precipitaciones pueden tener importantes consecuencias sobre la persistencia de las poblaciones de anfibios, especialmente en regiones semiáridas. En este estudio, utilizamos una serie temporal de 34 años en el centro de España para evaluar el efecto de tres variables climáticas sobre el éxito reproductivo del sapo corredor (*Epidalea calamita*) en charcas temporales.

Nuestros resultados muestran que la reproducción fue exitosa únicamente siete años (20.6 %). El éxito reproductivo está directamente relacionado con la precipitación acumulada en primavera, mientras que está relacionado negativamente con la temperatura y la evaporación durante la primavera. Este estudio destaca la importancia de conservar y restaurar los puntos de reproducción de los anfibios con el objetivo de minimizar los posibles impactos del cambio climático y la pérdida de hábitat.

Palabras clave

Biogeografía; variables climáticas; Comunidad de Madrid; conservación; *Epidalea calamita*; fenología; éxito reproductivo; series temporales; charcas temporales; condiciones meteorológicas

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1. INTRODUCTION

Amphibian species are globally threatened, with 40.7% of them (i.e. 2873 species) at some risk of extinction according to the most recent report of the International Union for Conservation of Nature (IUCN, 2024; Luedtke et al., 2023). Documented extinctions continue to increase in the last decades and their population trends are a cause of concern, with more than 40% of amphibian species experiencing worlwide demographic declines (Stuart et al., 2004). The main drivers of these declining trends are pollution, infection diseases, invasive species, habitat loss/transformation and climate change (Luedtke et al., 2023; Nunes et al., 2019).

Ectothermic organisms, such as amphibians, are more likely to be directly affected by climate change than other taxonomic groups due to their body temperature is dependent on the surrounding environmental conditions (McGrath & Lorenzen, 2010; Sinsch & Schäfer, 2016). In addition, the complex life cycle of amphibians, which encompasses both aquatic and terrestrial stages, makes them more vulnerable to climate change and habitat loss (Griffiths, 1997). In recent years, considerable progress has been made in understanding the effects of climate change on amphibians, with evidence of shifts in species geographical distribution, phenology and interactions with parasites (Li et al., 2013; Winter et al., 2016). The increasing frequency of droughts, rising temperatures and even small shifts in precipitation frequency associated with climate change can have a major impact on amphibian breeding habitats and, consequently, on the persistence of amphibian populations (Parra et al., 2021; Zacharias & Zamparas, 2010). For instance, one of the most famous and recent extinctions is that of the golden toad (*Incilius periglenes*), which lived in the Monteverde forest (Costa Rica) and has not been seen since 1989; for some authors it is the first extinction directly associated with climate change (Pounds et al., 1999).

The impacts of increasing temperatures and more variable precipitation regimes linked to climate change are especially relevant in arid and semi-arid regions, as the functioning of these ecosystems is strongly influenced by precipitation patterns (Miranda et al., 2011; Pontifes et al., 2018). During the last decades, Spain has suffered a progressive expansion of the arid and semi-arid climate zones, and climate change models predict a decrease in annual precipitation and higher frequency of extreme events (Chazarra Bernabé et al., 2023). As a result, increasing temperatures and decreasing precipitation may have a severe impact on amphibian populations in the semi-arid regions of central Spain.

In this study, we used a long term time series spanning 34 years in the Community of Madrid to evaluate the effect of three climatic variables on the reproductive success of the natterjack toad (*Epidalea calamita*) in temporary ponds, as well as changes over time. The aim of this work is to highlight the sensitive situation of amphibian populations in these semi-arid habitats. In addition, we will evaluate the reproductive phenology of the natterjack toad over the study period. We hypothesized that breeding will only be successful in the studied temporary ponds in wet years with low mean temperatures.

2. METHODS

2.1. TARGET SPECIES, STUDY AREA AND SAMPLING PROTOCOL

The natterjack toad *Epidalea calamita* (Laurenti, 1768) is native to western and central Europe, and it is distributed from the Iberian Peninsula in the southwest to western Russia in the east, reaching its northern range limit in Sweden and Estonia (Figure 1a) (IUCN, 2024; Saare & Rannap, 2021). The United Kingdom and south-west Ireland also have some scattered populations of this species. In Spain, it is present in most of the Iberian Peninsula, being scarce in the Cantabrian coast from Asturias to the Basque Country, and it is absent in the Balearic and Canary Islands (Gómez-Mestre, 2014) (Figure 1b). The natterjack toad can occupy a wide range of habitats, from coastal and arid areas to humid and mountainous regions above 2500 m altitude (Reques & Tejedo, 2002). It also inhabits anthropogenic areas linked to human activities such as quarries, industrial wastelands or farm ponds (Deflandre, 2021; Verdiell-Cubedo, 2012). It breeds preferably in temporary shallow sun-exposed ponds in open areas with bare ground and low or scarce vegetation. The selection of such ephemeral water bodies has a high risk of larval mortality due to desiccation of the aquatic environment (Cano-Barbacil & Cano, 2014). Thus, its reproductive phenology is closely linked to the rainfall regime, beginning in autumn in the Mediterranean regions of Spain, in winter in Andalusia and Extremadura, and in spring in the centre and north of the peninsula (Reques & Tejedo, 2002). The larval period is relatively short but very variable, and generally lasts between 24 and 54 days (Gómez-Mestre, 2014).

The study was conducted in central Spain, in the localities of Getafe, Valdemoro and Colmenar de Oreja (Community of Madrid, Spain). According to the latest Köppen classification of climate zones in Spain, this region has changed in recent decades from a hot summer Mediterranean climate (Csa) to a cold semi-arid steppe climate (BSk), due to a reduction in annual rainfall and an increase in mean temperatures (Chazarra Bernabé et al., 2023) (see also Figure 2). Three ephemeral pond clusters (hereafter sites) were monitored from 1991 to 2024 in the study area (Figure 1c). In all cases, the ponds are very shallow and usually last a few weeks. The Getafe site is located in the Getafe Air Base and consists of several temporary ponds formed in a bare area. The Valdemoro site consists of various temporary ponds that form along rural paths next to the Arroyo de la Cañada wetland. Similarly, the Colmenar de Oreja site consists of various temporary ponds that form on cultivated areas and rural paths next to the hypersaline wetland of Laguna de las Esteras.

The sampling campaigns were conducted during the breeding season of the natterjack toad, from February to July. All breeding ponds within the three study sites were visited on a weekly basis throughout the active breeding season to closely monitor the reproductive activity. Direct observations were made during each visit to determine the presence or absence of egg clutches and larvae. This routine continued until either larvae had reached the post-metamorphic stage or the pond had dried up. For each breeding event, detailed records were maintained, including the dates of each breeding event, whether reproductive success or failure was

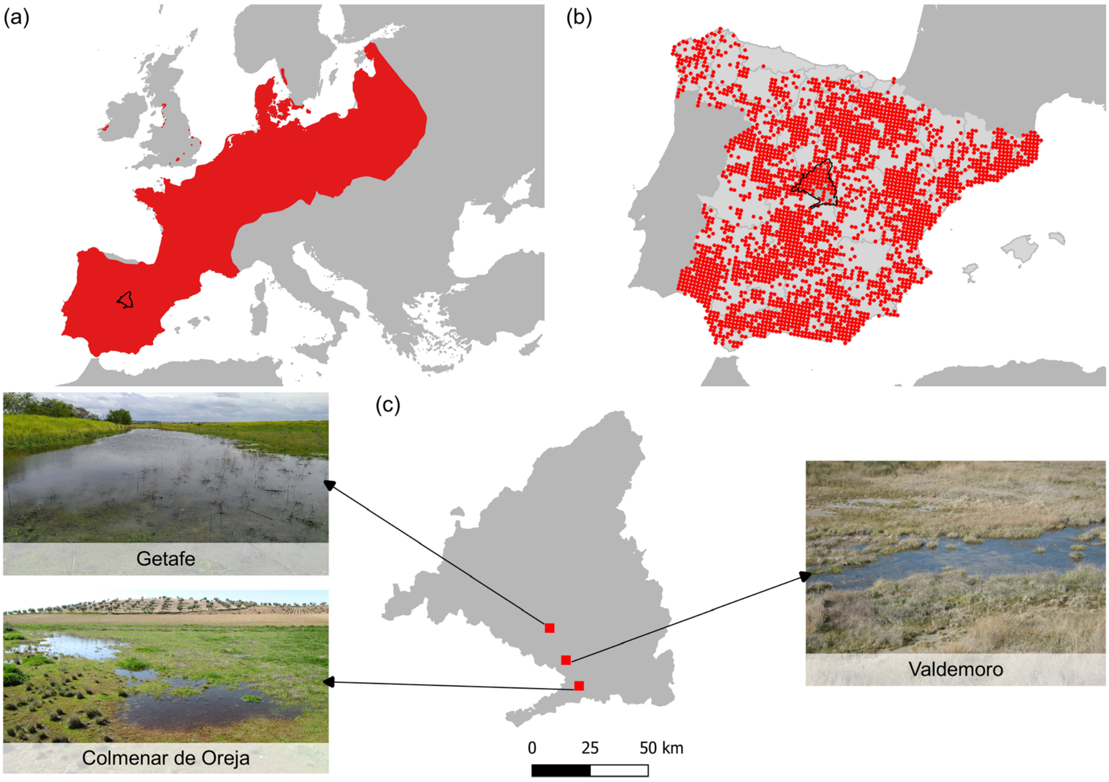


FIGURE 1. (A) GLOBAL DISTRIBUTION OF THE NATTERJACK TOAD *Epidalea calamita* (Laurenti, 1768). (B) DISTRIBUTION OF THE NATTERJACK TOAD IN SPAIN ACCORDING TO THE *MINISTERIO DE MEDIO AMBIENTE, Y MEDIO RURAL Y MARINO* (*INVENTARIO NACIONAL DE BIODIVERSIDAD 2007, ANFIBIOS*). (C) BREEDING POND CLUSTERS MONITORED IN THE COMMUNITY OF MADRID (SPAIN). Global distribution data and distribution in Spain were obtained from the International Union for Conservation of Nature and the Global Biodiversity Information Facility, respectively (GBIF.org, 2024; IUCN, 2024). The Community of Madrid is outlined in black in both (a) and (b)

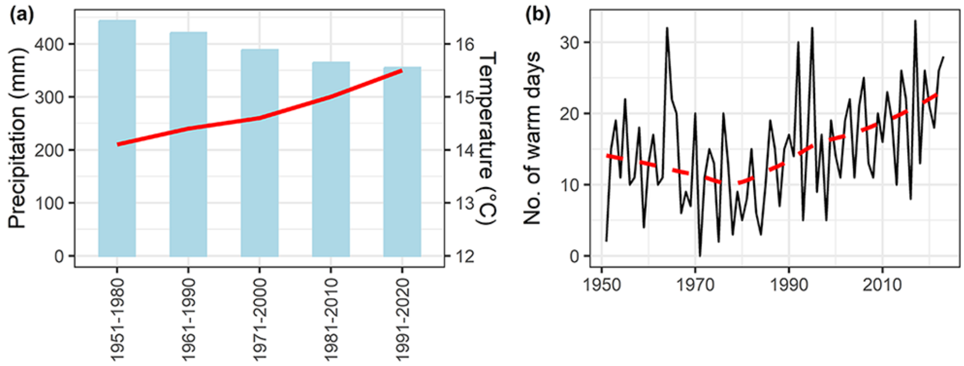


FIGURE 2. (A) EVOLUTION OF THE MEAN ANNUAL PRECIPITATION (BLUE BARS) AND THE MEAN ANNUAL TEMPERATURE (RED LINE) IN GETAFE (COMMUNITY OF MADRID, SPAIN) OVER THE LAST 70 YEARS. (B) EVOLUTION OF THE NUMBER OF SPRING WARM DAYS (I.E. MAXIMUM TEMPERATURE ≥ 25 °C) IN GETAFE OVER THE LAST 70 YEARS. THE RED DASHED LINE REPRESENT A LOESS (LOCALLY ESTIMATED SCATTERPLOT SMOOTHING) CURVE. Climatic data were obtained from the *Agencia Estatal de Meteorología* (AEMET)

observed, and the duration of the larval period. The sampling protocol and effort remained consistent throughout the 34-year study period.

2.2. CLIMATIC DATA AND STATISTICAL ANALYSIS

We obtained three climatic variables from the Getafe Meteorological Station (*Agencia Estatal de Meteorología*, AEMET) for the entire study period (i.e. from 1991 to 2024): accumulated spring precipitation (mm), mean spring temperature (°C), and spring evaporation (mm). The Getafe Meteorological Station is the nearest to the three sampled sites. For the purposes of this study, spring was defined as the period from March to May.

We used generalised linear models (GLM) with binomial distribution to relate the reproductive success of the natterjack toad to the three climatic variables. As the three variables are highly correlated among them ($|r| \geq 0.6$, $P < 0.001$), we ran three different models to assess individual relationships and to identify the best predictor of reproductive success. In order to assess a possible temporal trend, the sampling year was included as an explanatory variable in the models.

3. RESULTS

In 82.4% of the years (28 out of 34 years), temporary ponds formed at the study sites during the spring months, while in the remaining six years, no ponding occurred. Reproductive success in the temporary ponds was achieved in only seven years (20.6%). Breeding events took place between February and the first week of July (Figure 3).

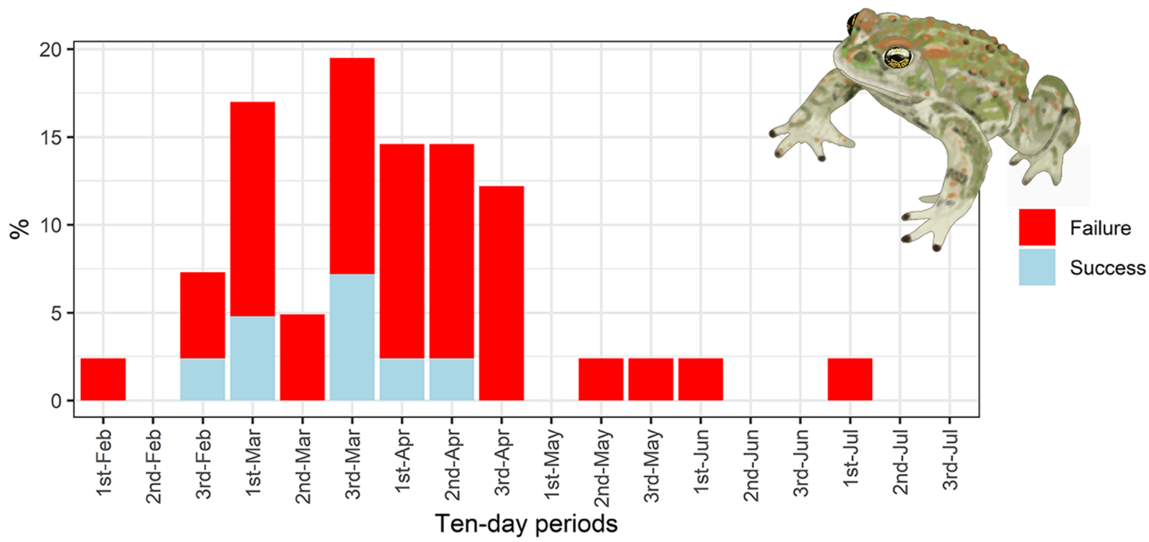


FIGURE 3. DISTRIBUTION OF SUCCESSFUL AND FAILED BREEDING EVENTS OF NATTERJACK TOAD (*Epidalea calamita*) RECORDED IN THE STUDY AREA

However, March and April accounted for 80.5% of the recorded breeding events. Early clutches (i.e. February and March) had a better chance of success compared to late clutches. We found that clutches laid from the last third of April onwards always failed. The larval period lasted between 39 and 78 days, with a mean duration of 52 days.

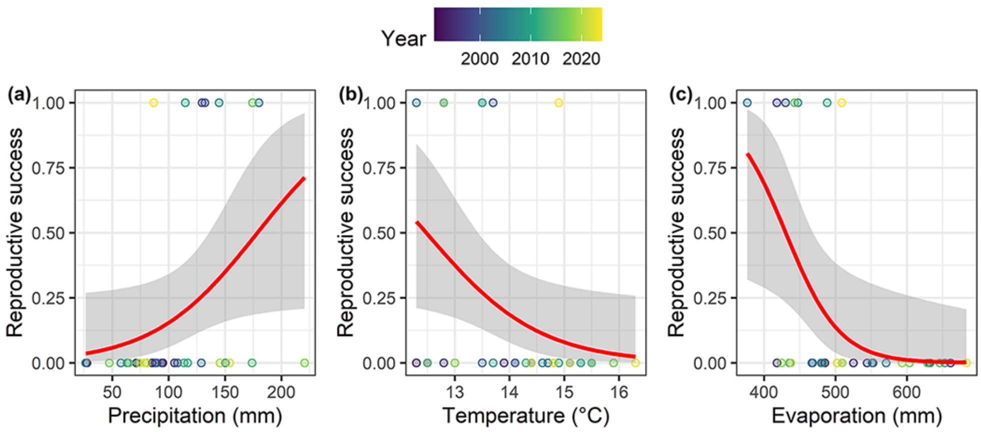


FIGURE 4. RELATIONSHIP BETWEEN REPRODUCTIVE SUCCESS OF NATTERJACK TOAD (*Epidalea calamita*) AND (A) ACCUMULATED SPRING PRECIPITATION (mm), (B) MEAN SPRING TEMPERATURE (°C), AND (C) SPRING EVAPORATION (mm). DOT COLOUR INDICATES YEAR OF SAMPLING. RED LINE SHOWS THE LOGISTIC REGRESSION, WHILE THE SHADOW REGION CORRESPONDS TO THE 95% CONFIDENCE LEVEL INTERVAL

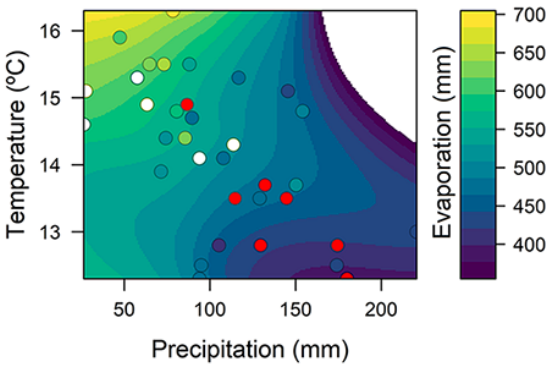
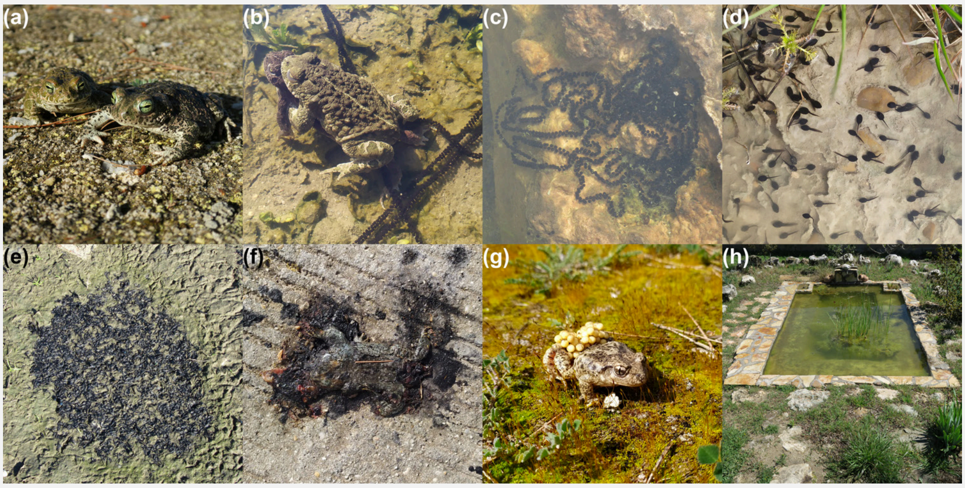


FIGURE 5. SURFACE PLOT RELATING ENVIRONMENTAL CONDITIONS WITH NATTERJACK TOAD (*Epidalea calamita*) REPRODUCTIVE SUCCESS IN TEMPORARY PONDS. HIGH SPRING PRECIPITATION AND LOW TEMPERATURES AND EVAPORATION ARE REQUIRED FOR SUCCESSFUL REPRODUCTION (INDICATED BY RED DOTS). YEARS IN WHICH NO PONDS WERE FORMED ARE REPRESENTED BY WHITE DOTS. THE COLOUR GRADIENT REPRESENTS VARYING LEVELS OF EVAPORATION

Our results showed that reproductive success of the natterjack toad is positively related to the accumulated spring precipitation (R^2 = 13.6%; P = 0.050; Figure 4a). By contrast, it is negatively related to mean spring temperature (R^2 = 20.8%; P = 0.022; Figure 4b) and spring evaporation (R^2 = 30.7%; P = 0.026; Figure 4c). The larvae did not complete metamorphosis in the temporary ponds studied when the spring accumulated precipitation was less than 75 mm, when the mean spring temperature was higher than 15 °C, or when the evaporation during the spring months exceeded the 550 mm (Figure 5). The best climatic indicator of reproductive success according to our models was evaporation, which explained more variation than the other two climatic predictors considered. However, we did not observe changes in the reproductive success of the natterjack toad over time ($P > 0.05$ in all models) during the study period.

4. DISCUSSION

Using a long-term time series spanning more than 30 years, this study highlights the vulnerability of amphibians to climate change and habitat loss, and the challenges that natterjack toads face when breeding in temporary ponds from arid and semi-arid ecosystems. Our results showed that the late formation of ponds, warm spring temperatures or low precipitation make it impossible for the natterjack toad to reproduce in these harsh environments, as they cause the premature desiccation of temporary ponds, and catastrophic mortality of natterjack tadpoles (see Box 1).



Box 1. (a) Couple of adult natterjack toads (*Epidalea calamita*). (b) Natterjack toads in amplexus in a temporary pond surrounded by spawn strings. (c) Strings of natterjack toads. (d) Tadpoles in a temporary pond in the study area. (e) Dead tadpoles in a desiccated pond. (f) Roadkill natterjack toad pregnant female; roadkill is one of the major threats to the natterjack toad in Spain. (g) Common midwife toad (*Alytes obstetricans*) male carrying an egg clutch; this species occasionally occupies habitats similar to those of the natterjack toad, but requires permanent water bodies to reproduce. (h) Restoring traditional fountains and creating small permanent ponds could help amphibian populations in semi-arid ecosystems.

Our observations showed that the larval period of the natterjack toad lasted from 39 to 78 days (mean: 52 days), compared to the 24-54 days reported by Gómez-Mestre (2014). This result indicates that this species needs temporary ponds that hold water for at least a month and a half for successful reproduction. However, these conditions were not met in most years, leading to failure in 79.4% of the breeding seasons.

Our results indicated that the great variation in breeding success recorded can be mainly attributed to meteorological factors. Most convincing was the negative relationship between spring evaporation and reproductive success, as well as the positive relationship between accumulated precipitation between March and May and toadlet production. Previous studies have also reported that the observed decline in spawning and metamorphosis success of the natterjack toad is closely linked to declining spring rainfall (Smith & Skelcher, 2019). Other environmental factors such as wind velocity, humidity and infiltration can also favour the early desiccation of this shallow temporary ponds, and affect the reproductive success of the natterjack toad.

In agreement with previous works, our results suggest that successful breeding is increasingly reliant on management actions focused on create ponds that hold water long enough for metamorphosis to occur (Smith & Skelcher, 2019). Thus, our study highlights the relevance of artificial water bodies (Caballero-Díaz et al., 2020, 2022, 2024) and naturalised quarries (Deflandre, 2021; Gómez-Ramírez et al., 2023) in semi-arid regions, particularly in those affected by habitat loss and fragmentation (Cano-Barbacil & Cano, 2014; Gómez-Ramírez et al., 2023). Management efforts should be focused on preserve and restore this vital environments for freshwater fauna and enhance habitat connectivity (Cano-Barbacil et al., 2021; Cano-Barbacil & Cano, 2015; Sinsch, 1992).

Under the climate scenarios available for the 21st century, the geographic distribution of the natterjack toad could be reduced due to changing environmental conditions. Reduced precipitation and rising temperatures could lead to the extinction of some populations (see e.g. Aragón et al., 2010; Cano-Barbacil et al., 2024; Hernández-Manrique et al., 2013). In fact, Araújo et al. (2011) projected contractions in the current potential distribution of the natterjack toad of between 58% and 59% in 2041-2070. According to this study, some of the most affected regions would be Castilla-La Mancha and the south of the Community of Madrid. In addition, negative impact of wildfires could increase with climate change, as shifts in temperature and precipitation regimes are also known to modify fire dynamics towards larger and more intense fires (Muñoz et al., 2019). Previous studies showed that future scenarios of increased recurrence of megafires could reduce the breeding activity of amphibians and can threaten the persistence of their populations (Muñoz et al., 2019). Similarly, climate change, through shifts in water clarity, can also impact freshwater ecosystems profoundly and the reproductive success of amphibians and other aquatic organisms (Piper et al., 2024).

5. CONCLUSIONS

Our study revealed that climatic factors are key to understand the reproductive success of the natterjack toad in temporary habitats, as the late formation of ponds, warm spring temperatures or low precipitation can cause their premature desiccation, and high mortality rates of tadpoles. These results highlight the importance of conserving and restoring amphibian breeding habitats, especially in arid and semi-arid regions affected by human activities, where natural breeding sites are becoming increasingly scarce due to climate and land use changes. If the current trend of increasing temperatures and decreasing precipitation continues, it is possible that some populations of the natterjack toad will disappear in central Spain over the next few decades, reducing its current distribution range.

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