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# Amphibian richness along modified riparian areas of central Mexico: conservation priorities

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## Abstract

**Background:** Land-use change frequently affects faunistic populations and communities. To achieve successful conservation strategies, we need suitable information about species distribution and the causes of extinction risk. Many amphibian species depend on riparian vegetation to complete their life cycles. About 41% of amphibian species are globally threatened, and accurate estimations of population size, species richness and the identification of critical habitats are urgently needed worldwide. To evaluate the magnitude of changes in species richness and demography, estimations that include detection probability are necessary. In this study, we employed multi-species occupancy models to estimate detection probability and the effect of land cover type (i.e., cropland, artificial pasture, secondary and mature forest) in a 500-m radius on the occupancy probability and richness of diurnal amphibians in 60 riparian zones in the state of Michoacán in central Mexico. Furthermore, we evaluated the potential of the endemic salamander *Ambystoma ordinarius* as a flagship species for the conservation of other native amphibian species.

**Results:** We registered a total of 20 amphibian species in the diurnal assemblage, of which 10 species are considered at risk of extinction. We found that cropland was the most important land-use type for explaining amphibian distribution in riparian zones, with negative effects on most amphibian species. We found no differences in species richness between zones with and without *A. ordinarius*. In riparian zones occupied by *A. ordinarius*, however, we found a higher number of species at risk of extinction.

**Conclusions:** Our findings showed negative effects of croplands on the distribution of most amphibian species. The riparian zones are important for the maintenance of native diurnal amphibian communities and *A. ordinarius* can act as a flagship species for the conservation of threatened amphibian species.

**Keywords:** Flagship species, Habitat quality, Occupancy models, Salamanders, Threatened species

## Background

Human population growth in urban centers and the consequent demand for resources are the main drivers of environmental degradation and land-use change (Grimm et al. 2008; Seto et al. 2012). Land-use changes frequently cause a decrease in the population size of native species, a loss of local populations, and the replacement of

disturbance-sensitive species with disturbance-tolerant species (Fahrig 2003; Socolar et al. 2016). To mitigate the negative effects of land-use change, conservation strategies prioritize the protection of areas with the aim of holding the highest species richness, with a greater number of threatened species or with fundamental habitats for the species (e.g., breeding zones or migratory routes; Arponen 2012; Asaad et al. 2017). Alternatively, to protect the distribution area of flagship species, we can preserve other species sharing the same space or even full ecosystems (Barua et al. 2011; Bride et al. 2008). Nevertheless, we require suitable information regarding species

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distribution and threats to accomplish successful conservation strategies (Lambeck 1997).

Reliable estimations about species' responses to environmental changes require the evaluation of ecological (e.g., abundance and distribution) and sampling (detection probability) aspects (Kéry and Royle 2008; Guillera-Aroita 2017). By using occupancy models, the assessment of both aspects provides the accurate estimations of species distribution (Kéry et al. 2010), abundance (Ocock et al. 2016), metapopulation dynamics (Heard et al. 2013) and specific richness patterns (Grant et al. 2013). In addition, occupancy patterns of species associated with landscape attributes, including the proportion of mature vegetation, the proportion of different land uses, and altitude, have been described through these models (Zipkin et al. 2009; McGrann and Furnas 2016; Valentine et al. 2020). Therefore, the use of occupancy models is an important tool for assessing the response of species to land-use change and species richness patterns, which are critical aspects when considering the conservation of species at risk of extinction (Devarajan et al. 2020).

Amphibians are very sensitive to environmental degradation, ca. 41% of known species are globally threatened (IUCN 2021). These vertebrates are vulnerable to land-use change because many species depend on the connection between aquatic and terrestrial habitats to complete their life cycles (Becker et al. 2007, 2010). Therefore, the vegetation adjacent to water bodies (i.e., riparian vegetation) is important to many amphibian species as this habitat provides suitable conditions (e.g., high environmental humidity) for reproduction and maintenance of their populations (Rodríguez-Mendoza and Pineda 2010; Suazo-Ortuño et al. 2011). Furthermore, riparian vegetation provides food and shelter for amphibians, mitigating the negative conditions associated with land-use change (Muenz et al. 2006; Boissinot et al. 2015). Thus, by considering the high levels of extinction risk for many amphibian species, conservation strategies require reliable estimations of species distributions as well as the identification of critical areas for their conservation.

In the state of Michoacán, Mexico, the physiographic provinces Neovolcanic Axis and the Balsas Depression co-occur. Both provinces are recognized as centers of diversification and endemism for amphibians (Flores-Villela and Goyenechea 2003; Urbina-Cardona and Flores-Villela 2010). In this region, 51 amphibian species have been described, 25 of which are at risk of extinction (Alvarado-Díaz et al. 2013). As a consequence of agriculture and livestock activities, only 60% of Michoacán's original vegetation coverage remains relatively well preserved (INEGI 2017). Therefore, for the conservation of Michoacán amphibians, it is fundamental to recognize

the factors that define the patterns of amphibian richness and prioritize areas for their conservation.

Among the amphibians in Michoacán, *Ambystoma ordinarium* is distributed in riparian areas of the Neovolcanic Axis and the Balsas Depression (Escalera-Vázquez et al. 2018). Thus, the distribution area of this salamander overlaps with numerous amphibian species. Because salamanders of the genus *Ambystoma* are popular in Mexico, *A. ordinarium* (a threatened species) could be granted with flagship species category (IUCN 2021). The objective of this study was to describe the environmental factors influencing diurnal amphibian richness in order to prioritize riparian areas for conservation and to assess the value of *A. ordinarium* as a flagship species in northeastern Michoacán. In this context, we evaluated the following: (i) several environmental variables in riparian zones at different landscapes potentially associated with amphibian distribution; (ii) for each riparian assemblage we estimated the number of amphibian species; (iii) as well as species considered at risk of extinction, and (iv) we evaluated the species richness and number of threatened species associated with the presence of *A. ordinarium*.

## Methods

### Study area

To define the study area, we simultaneously used the *A. ordinarium* area of occupancy estimated by the IUCN SSC Amphibian Specialist Group (2015) and its potential distribution area estimated by Escalera-Vázquez et al. (2018), in northeastern Michoacán, Mexico. In this region, the original vegetation was coniferous forest, mixed conifer and oak forest, cloud mountain forest and deciduous forest (Rzedowski 2006). Most original forest, however, has been replaced by croplands, cattle pastures, and tree orchards (Ihl and Bautista-Zúñiga 2017; Bonilla-Moheno and Aide 2020). Furthermore, there are patches of secondary forest regrowth after agricultural activities (Bonilla-Moheno and Aide 2020). The altitude in this region varies between 700 and 3000 m a.s.l., the annual rainfall ranges from 600 to 1500 mm, and the annual average temperature ranges from 10 to 26 °C (Cuervo-Robayo et al. 2014a, b).

A total of 47 amphibian species have been associated with riparian vegetation in northeastern Michoacán (Alvarado-Díaz et al. 2013). In the study region, amphibian assemblages in riparian vegetation, including *A. ordinarium*, are composed of (i) species dependent on high environmental humidity for reproduction (i.e., *Craugastor* spp., *Eleutherodactylus* spp., *Pseudoeurycea* spp., and *Isthmura bellii*); (ii) species associated with riparian vegetation throughout the year (i.e., *Lithobates* spp. and species of the Hylidae family); and (iii) species with

an explosive breeding mode that inhabit riparian vegetation at particular periods of the year (i.e., *Incilius* spp. and *Rhinella horribilis*; Alvarado-Díaz et al. 2013).

### Sampling design

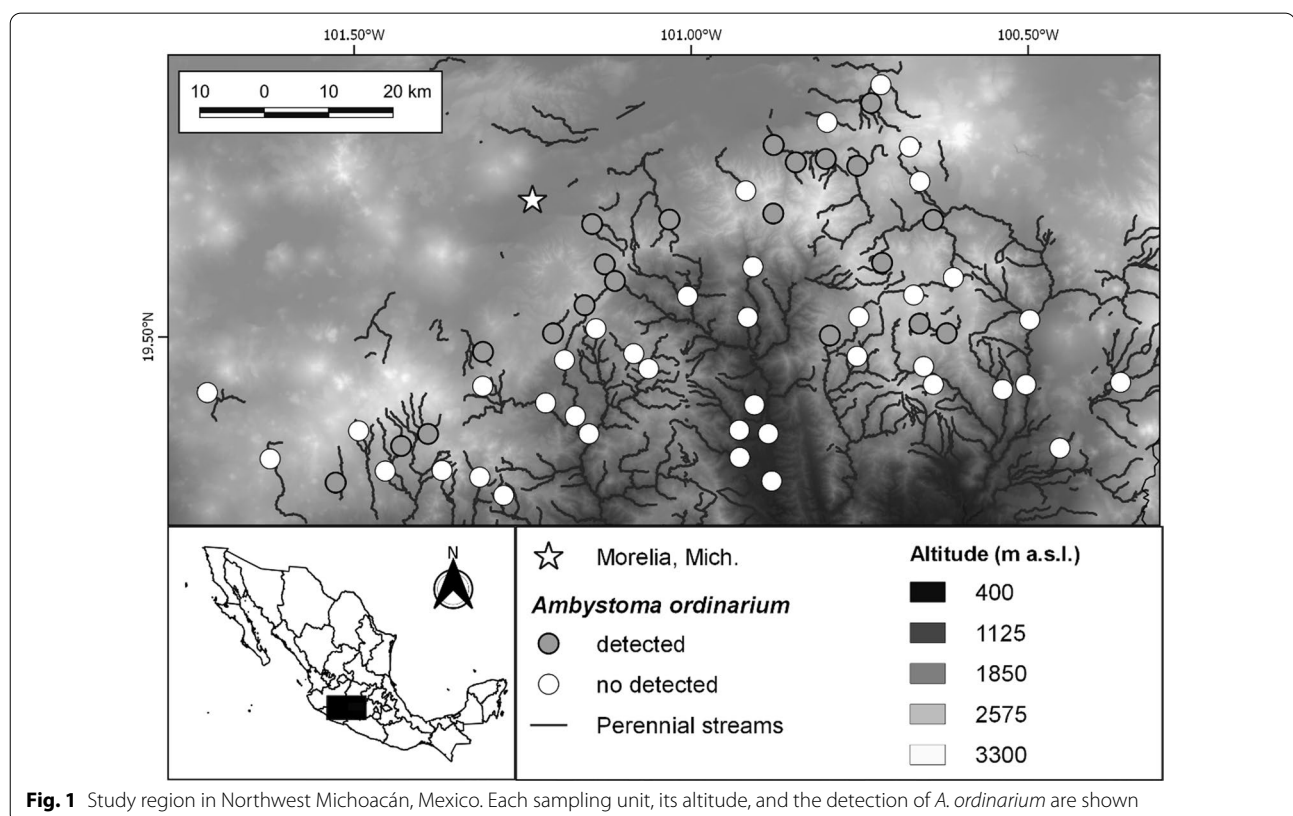
To characterize the riparian assemblages in the study area, we carried out visual encounter surveys in 60 sampling units (Crump and Scott 1994). The sampling units consisted of 50 m long stream sections with a  $50 \times 25$  m sampling plot located along each stream section, at the left or right of the riverbank (chosen randomly) towards uplands. To ensure the spatial independence among riparian zones, we only selected stream sections that were at least 3 km apart, considering the average dispersal capacity of amphibians (Fig. 1; Rittenhouse and Semlitsch 2007). Additionally, to represent the environmental variation of the region, we selected stream sections with different proportion of mature forest along an altitudinal gradient (700 and 3000 m a.s.l.). The proportion of mature forest in the sampling units ranged between 0.02 and 0.85.

From February 2018 to October 2019, we conducted 12 sampling events in each sampling unit. The sampling effort per sampling unit was 40 min/person per sampling event. Each event lasted 12 days on average. To record the variation in the environmental conditions, the period

between sampling events was 21–45 days. Because of unsafe conditions, the search for amphibians was only diurnal, between 9:00 AM and 6:00 PM. Therefore, the amphibian assemblages we studied only included diurnal species. The order and period of the day in which we sampled the units differed in each sampling event. The search for amphibians was performed through the following methods: (i) checking terrestrial microhabitats, including tree hollows, under logs and rocks, leaf litter and riverbanks, and (ii) checking aquatic microhabitats, including the bottom of the stream channel and among roots and rocks, using a 30-cm-diameter hand net. We only recorded juveniles and adults and identified to species level all specimens collected in the field. Except for those threatened species, one individual of each species was deposited in the herpetological collection of the Universidad Michoacana de San Nicolás de Hidalgo. Scientific collecting permit number SGPA/DGVS/001450/18 was granted by SEMARNAT.

### Environmental variables

To characterize the response of the diurnal amphibian assemblage to environmental variables, we recorded the air temperature (°C), air relative humidity (%) and date at each sampling unit during all the sampling events (with the Julian calendar). Temperature (temp) and humidity



(humd) were recorded with a Bacharach 0012-7012 psychrometer. We recorded landscape variables that have been associated with amphibian presence (Moreira et al. 2016; Ribeiro et al. 2018; Siqueira et al. 2021). Within a 500-m radius from the center of each sampling unit, we estimated the proportion of eight land-use and land cover types, including the following: water bodies, bare ground, urban settlements, orchards, croplands, artificial pasture, secondary and mature forest, as well as altitude (m a.s.l.). The 500-m radius was selected by considering the standard estimate of the amphibians' core habitat average (Rittenhouse and Semlitsch 2007). Land-use and land cover types were estimated using Sentinel-2 satellite photographs from February 2018 (United States Geological Survey, USGS). The photographs were processed with QGIS software, version 2.8.2 (Quantum GIS Development Team 2014) and its complement Semi-Automatic Classification Plugin (Gémes et al. 2016).

### Statistical analysis

To estimate amphibian species' response to different environmental variables while considering the differences in inter-species detectability, we implemented Multi-Species Occupancy Models (MSOMs) with data augmentation, using Bayesian inference (Kéry and Royle 2009). We defined the posterior distribution of simulate metacommunity size as  $N = n + \sum_{i=k}^{nz} w_{n+k}$ , where  $n$  is the detected species,  $nz$  is the number of species that we never detected added to the data set (as zero histories) and  $w$  is the occurrence of each species in the metacommunity. We specified the  $w$  value for each  $k$  species in the metacommunity as  $w_k \sim \text{Bernoulli}(\Omega)$ , where  $\Omega$  is the probability that  $k$  species belongs to the  $N$  size metacommunity. We specified the occurrence of each  $k$  species, imperfectly observed, at the unit  $i$  as  $z_{ik} \sim \text{Bernoulli}(\psi_{ik} w_k)$ , where  $\psi_{ik}$  is the probability that  $k$  species will occupy the unit  $i$ . Finally, we defined the detection process for each species in each sampling unit as  $y_{ijk} \sim \text{Bernoulli}(p_{ijk} z_{ik})$ , where  $y_{ijk}$  is the detection/no detection history at the  $j$ th sampling event, with the detection probability  $p_{ijk}$ .

We established the upper limit of the metacommunity size ( $M=47$ ) considering the species reported for the region (Alvarado-Díaz et al. 2013). We modeled species-specific occupancy and detection probability based on explanatory variables (cov) specified as  $\text{logit}(\psi_{ik}) = \alpha_{\psi, k} + \beta_{\psi, \text{cov}, k} * \text{cov}_k$  and  $\text{logit}(p_{ijk}) = \alpha_{p, k} + \beta_{p, \text{cov}, k} * \text{cov}_{jk}$ . We estimated how the metacommunity responds to each explanatory variable by considering species-specific parameters as independent random effects ( $\alpha$  and  $\beta$ ). Thus,  $\alpha$  and  $\beta$  are defined as  $\alpha_{\theta, i} \sim \text{Normal}(\mu_{\alpha_{\theta}}, \sigma_{\alpha_{\theta}}^2)$  and  $\beta_{\theta, \text{cov}, i} \sim \text{Normal}(\mu_{\beta_{\theta, \text{cov}}}, \sigma_{\beta_{\theta, \text{cov}}}^2)$ , with  $\theta = (\psi, p)$ , respectively (Kéry and Royle 2009).

### Model construction

We standardized explanatory variables with mean zero and a standard deviation equal to 1. The standardization allows consistency among established prior distributions with all parameters, enabling the assessment between the effects of explanatory variables and a faster convergence of the posterior distribution probabilities of each parameter (Broms et al. 2016). We developed the models resulting from the combination of the following explanatory variables: (i) to estimate detection probability, we considered sampling variables; (ii) to model the detection probability, we used linear responses as the logistic regression is expressed as a sigmoidal form and can help to identify the optimal value from some section of the environmental gradient (Bio et al. 1998). We avoided the use of temperature and humidity in the same model since they were highly correlated ( $r=0.64$ ) but included both variables separately in the same number of models. To estimate the probability of occupancy, we considered four types of land-use and land cover types with higher extension along study area: mature and secondary forest (regrowth vegetation), cropland and artificial pasture (Additional file 1: Appendix S1), and the altitude of each sampling unit. To estimate the mature forest effect on species' occupancy probability, we only considered a linear response. In addition, to estimate the species occupancy probability and their response to land-use types and altitude in the models, we used both linear and quadratic effects. This was done to consider the probable amphibian occupancy curvilinear association with covariables, explicitly, maximum or minimum occupancy estimations approaching an intermediate value of variables (Kéry and Royle 2009; Holoubek and Jensen 2015; Gao and Carmel 2020). The variables employed, the structure and hypothesis for each model are presented in Table 1.

We developed the models using weakly informative priors, for  $\Omega$  we used a uniform distribution (0, 1). For  $\mu_{\alpha_{\theta}}$  and  $\mu_{\beta_{\theta, \text{cov}}}$  we used a normal distribution with mean zero and a standard deviation of 0.01, and uniform distribution (0, 10) for its accuracy  $\sigma_{\alpha_{\theta}}^2$  and  $\sigma_{\beta_{\theta, \text{cov}}}^2$ . We developed a MSOM in NIMBLE 0.10.1 (de Valpine et al. 2020), which is an R package for the Bayesian analysis, using a Markov chain Monte Carlo (MCMC) algorithm. We estimated the posterior probability distributions of model parameters from three MCMCs with 300,000 iterations. In order to reduce the autocorrelation of the chains, we discarded the first 150,000 iterations as burn-in and a thinning rate of 30. At the end, we employed 15,000 samples for the estimation of posterior probability distributions of each parameter. We assessed the convergence of values among the three chains by using the Gelman–Rubin statistic ( $\hat{R}$ ; Gelman and Rubin 1992) and by visually inspecting and comparing each MCMC chain's sample traceplots.



**Table 1** Multi-species occupancy models developed for explaining occupancy patterns of amphibians in Northwest Michoacán riparian zones

Model	Occupancy variables	Detection variables	Hypothesis and predictions
Ambystoma	(crops) + (alt)	(temp)	The amphibian species in the study region are mostly tolerant to agricultural coverages and have preferences for high-altitude zones. Thus, every amphibian species in the study region shows similar responses to land-use changes as <i>Ambystoma ordinarius</i> (Oropeza-Sánchez et al. 2021)
Altitude	(alt) + (alt) <sup>2</sup>	(humd) + (date)	The study region is inhabited by species from two physiographic provinces with distinct altitude features; therefore, most amphibian species co-occur at intermediate altitudes with the highest richness (Siqueira et al. 2016)
Forest	(forest)	(temp) + (date)	The amphibian community, in the study region, is represented by species mostly adapted to the original natural environments. Therefore, greatest species richness would be found in landscapes with greater proportion of mature forest (Zipkin et al. 2009)
Secondary	(sec) + (sec) <sup>2</sup>	(temp)	The amphibian community is composed by resilient species capable of inhabiting secondary vegetation regrowth. Therefore, greater species richness would be recorded in zones with high proportion of secondary forest (Díaz-García et al. 2017)
Crops	(crop) + (crop) <sup>2</sup>	(humd)	The amphibian community is composed by species with high or moderate tolerance to agricultural landscapes. Therefore, highest species richness would be recorded in zones with high to intermediate proportion of cropland (Ribeiro et al. 2018)
Livestock	(lives) + (lives) <sup>2</sup>	(humd)	The amphibian community is composed by species with high or moderate tolerance to artificial pasture in the landscape. Therefore, highest species richness would be recorded in zones with high or intermediate proportion of pasture (Moreira et al. 2016)

We show the environmental variables for explaining each parameter (detection or occupancy), their structure and the hypothesis represented. Altitude = alt, mature forest = forest, secondary forest = sec, cropland = crops, artificial pasture = lives, temperature = temp, relative humidity = humd, date = date

and posterior sampling distributions. We considered an  $\hat{R}$  value close to 1 as evidence of the chains' convergence ( $\hat{R} \leq 1.1$  as an acceptable value; Gelman and Rubin 1992; Doherty et al. 2020). To compare the model support and perform model selection, we used the Watanabe–Akaike Information Criterion (WAIC; Watanabe 2010; Hooten and Hobbs 2015). In addition, to assess the sensitivity of the estimate of the potential number of species ( $N$ ) and their credibility intervals to 95% (95% CI) to the data augmentation, we verified the values of  $N$  in models where  $M = 150$  (Royle and Dorazio 2012).

Considering the  $z_{ik}$  values of the model with greater support, we defined which sampling units were occupied by each species. The species richness in each sampling unit (site-specific) was calculated as the sum of the estimated number of species present for each unit (the  $z$  values). Furthermore, to calculate the site-specific number of species at risk,  $z_{ik}$  values were calculated using species results with an Environmental Vulnerability Score (EVS)  $\geq 12$  (Alvarado-Díaz et al. 2013; Wilson et al. 2013). The EVS evaluates species vulnerability to extinction using distribution data and traits associated with life history. In the study area, the EVS of amphibian species oscillates from 3 to 17, with high values representing higher risk (Wilson and McCranie 2004; Wilson et al. 2013).

Finally, we evaluated the potential of *A. ordinarius* as a flagship species. To do so, we compared the number of species and threatened species between units where *A. ordinarius* was detected and where it was not detected.

The number of site-specific species and species at risk values were compared using generalized linear models with Poisson distribution from the gmodels package (Warnes et al. 2018). For the set of units where *A. ordinarius* was detected, the cumulative number of species and species at risk was estimated. To validate the comparison of cumulative values from the set of units where *A. ordinarius* was not detected, we randomly selected the same number of units with *A. ordinarius* detections (21 units). This process was performed 100 times in total. From the data obtained, we evaluated differences with the one-sample  $t$ -test. All analyses were run in the R software version 4.0 (R Core Team 2020). Details of the implemented code are shown in the supplementary information (Additional file 2: Appendix S2).

## Results

We registered a total of 20 amphibian species in the diurnal assemblage. Ten species are considered at risk of extinction. The number of detected species by sampling unit varied from 0 to 5 (Additional file 3: Appendix S3). The salamander *Ambystoma ordinarius* and the frog *Lithobates neovolcanicus* were the species with the highest number of units with detections. The top two models describing the diurnal amphibian data based on the lowest WAIC values were *Ambystoma* and *Crops* (Table 2). The *Ambystoma* model, however, was more sensitive than the *Crops* model to data augmentation because it contains more uncertainty in metacommunity size predicted values ( $N$ ; see Table 2). This indicates that the

**Table 2** Multi-species occupancy models, considering different environmental variables, developed for explaining the amphibian occupancy patterns in riparian zones of Northwest Michoacán, Mexico

Model	WAIC	N (2.5–97.5% CI)	
		M = 47	M = 150
<b>Crops</b>	<b>1869.10</b>	<b>25 (20–42)</b>	<b>26 (20–49)</b>
Ambystoma	1870.46	32 (21–46)	53 (23–141)
Livestock	1875.49	25 (20–44)	25 (20–53)
Secondary	1878.72	29 (21–46)	33 (21–121)
Forest	1889.80	27 (21–44)	26 (20–65)
Altitude	1900.98	38 (24–47)	76 (28–145)

We show the Watanabe–Akaike Information Criteria value (WAIC) and the potential number of species ( $N$ ); when the upper limit ( $M$ ) is 47 and 150, and their 95% credibility intervals. Bold letters correspond to the model with greater support and more accurate estimation

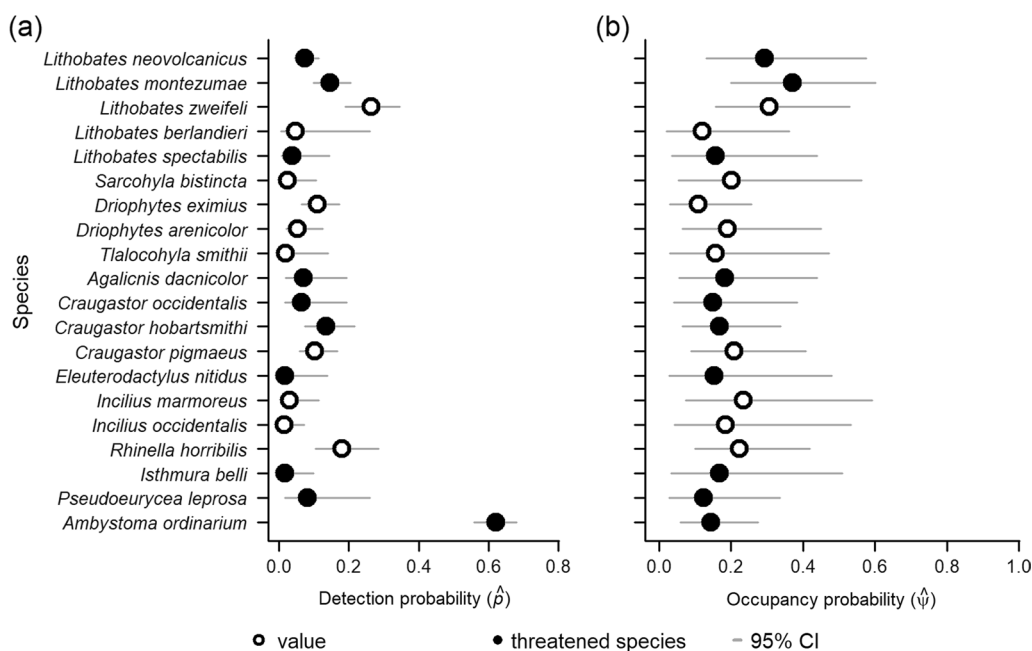
*Crops* model is better supported than the *Ambystoma* model by the data. Thus, to estimate the diurnal amphibian response to environmental variables and species richness, we used the *Crops* model.

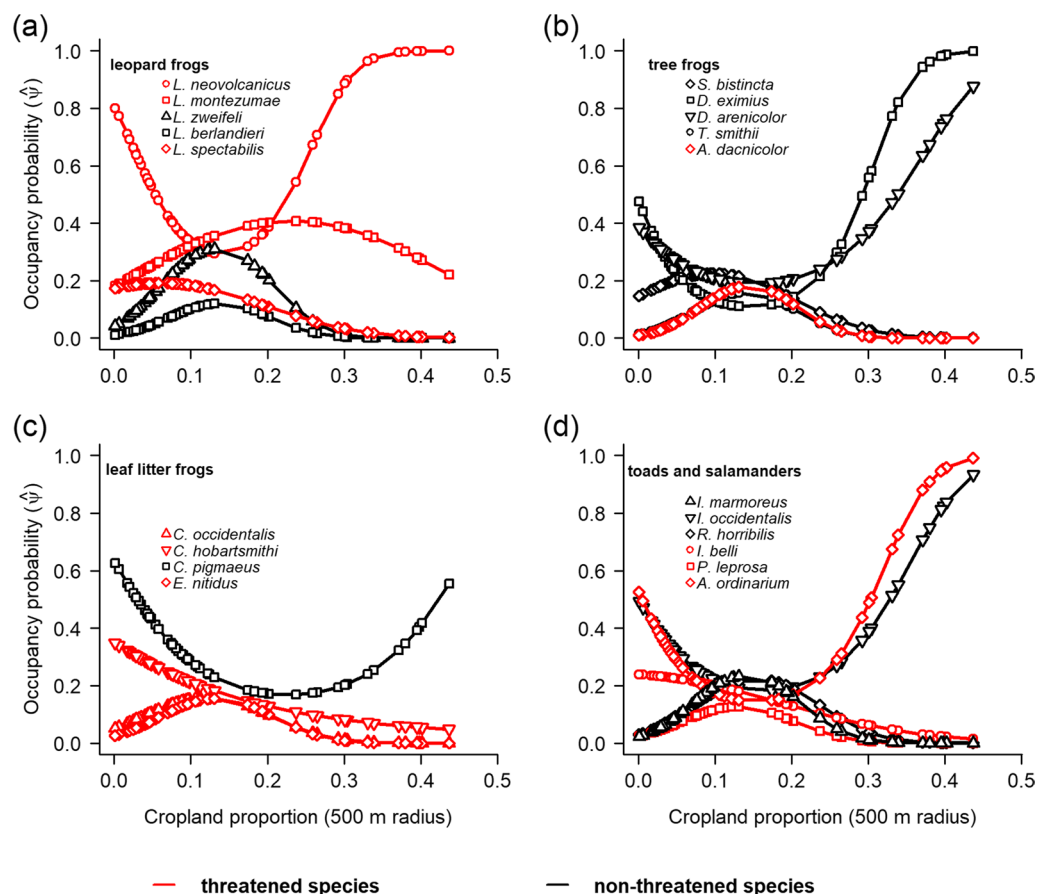
The *Crops* model included the variables humidity ( $\mu_{\beta_{p,humd}}$ ) to explain the metacommunity probability detection and the linear ( $\mu_{\beta_{\psi,crops}}$ ) and quadratic effect of cropland ( $\mu_{\beta_{\psi,crops^2}}$ ) to explain the metacommunity occupancy probability. The median value of metacommunity size from the *Crops* model was 25 species (95% CI=20–42), which means that in addition to the 20

species detected five undetected species should be part of this metacommunity. The estimate of  $N$  proved to be unaffected by data augmentation compared with other models, as it did not vary considerably by increasing the upper limit of potential species to 150 ( $N$  (95% CI)=26 (20–49)). Additionally, the *Crops* model estimated a detection probability ( $\hat{p}$ ) < 0.06 for three of ten threatened species (Fig. 2a), but none of these species had a very imprecise occupancy probability ( $\hat{\psi}$ ; 95% CI with an amplitude lower than 0.5; Fig. 2b).

Air humidity was not a reliable predictor for the estimate detection probability of any species by integrating the zero value into 95% CI (Additional file 4: Appendix S4). The metacommunity detection probability response to humidity was  $-0.1$  (95% CI =  $-0.27$  to  $0.05$ ). The linear effect of crops coverage did not represent a reliable predictor for any amphibian occupancy probability. The linear effect of cropland on the metacommunity ( $\mu_{\beta_{\psi,crops}}$ ) had a coefficient of  $-0.26$  (95% CI =  $-0.84$  to  $0.22$ ; Additional file 4: Appendix S4). The quadratic effect of crops had a strong response in six species, a negative coefficient in *Lithobates zweifeli*, *Tlalocohyla smithii*, and *Rhinella horribilis*, and a positive coefficient in *L. neovolcanicus*, *Dryophytes eximius* and *A. ordinarium*. In addition, the coefficient for the metacommunity ( $\mu_{\beta_{\psi,crops^2}}$ ) was  $-0.82$  ( $-2.2$  to  $0.14$ ; Additional file 4: Appendix S4).

For the *Crops* model, we explored the response to cropland proportion in the landscape for each species' occupancy probability ( $\hat{\psi}$ ) (Fig. 3). We predicted

**Fig. 2** Mean probability estimated of **a** detection and **b** occupancy for each amphibian species in all sampling units

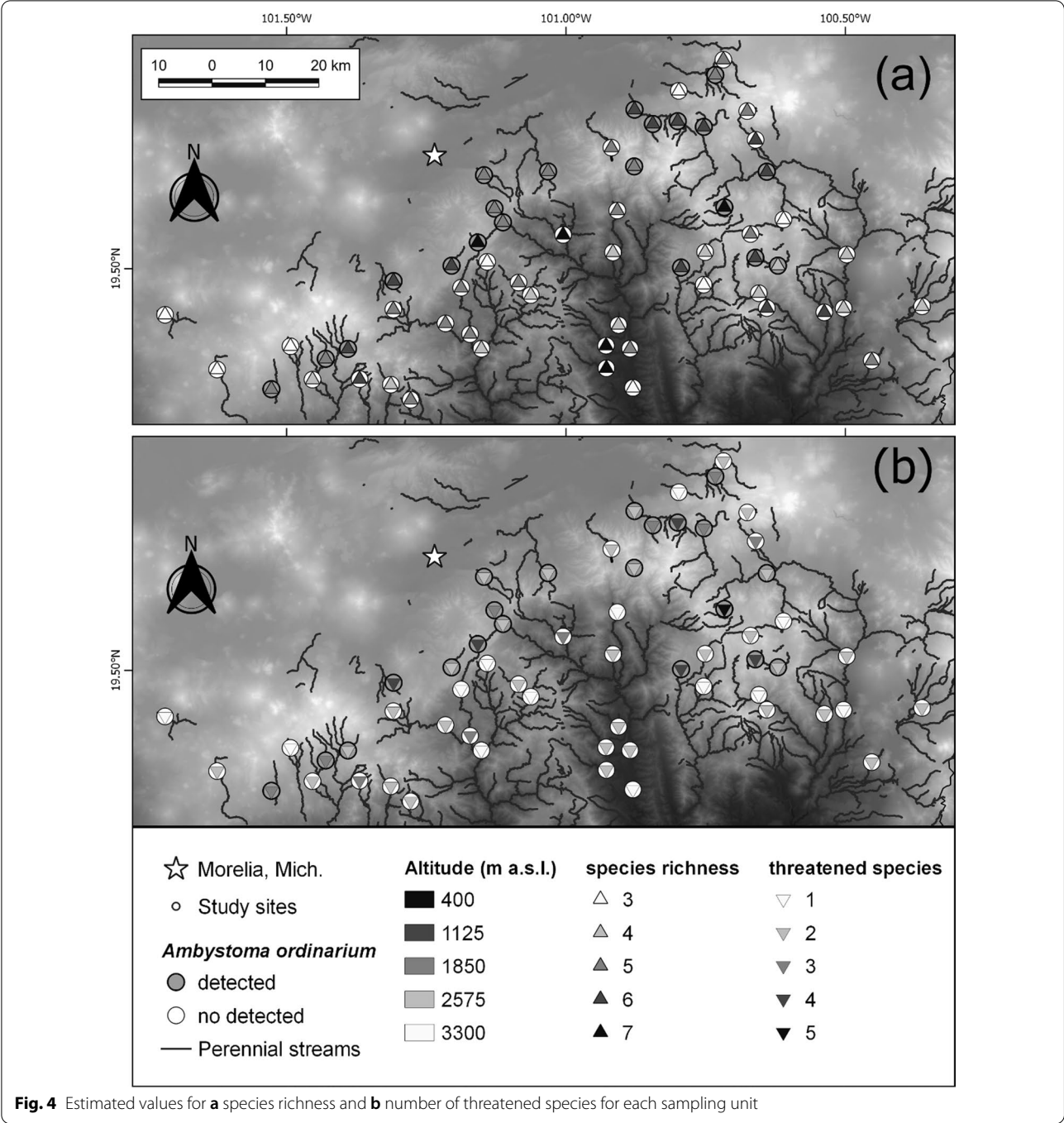


**Fig. 3** Linear and quadratic effect of cropland proportion on occupancy of 20 detected amphibian species. The figure shows the response of each species in the following categories **a** leopard frogs, **b** tree frogs, **c** leaf litter frogs and **d** toads and salamanders

the highest value of  $\hat{\psi}$  in the units with a higher proportion of cropland (near to 0.4) for *L. neovolcanicus*, *D. eximius*, *Dryophytes arenicolor*, *Incilius occidentalis* and *A. ordinarius*. In units with a crops proportion lower than 0.2, we predicted the highest value of  $\hat{\psi}$  for *Lithobates spectabilis*, *Craugastor hobartsmithi* and *Ithsmura bellii*. Most species (*L. zweifeli*, *Lithobates berlandieri*, *Sarcohylla bistincta*, *T. smithii*, *Agalychnis dacnicolor*, *Craugastor occidentalis*, *Eleutherodactylus nitidus*, *Incilius marmoreus*, *R. horribilis* and *Pseudoeurycea leprosa*) had a high value of  $\hat{\psi}$  in sampling units with crops proportions between 0.1 and 0.2, with a decrease as they approached 0.45 proportion. In units with an intermediate cropland proportion (between 0.2 and 0.3), *Lithobates montezumae* presented its highest  $\hat{\psi}$  value. In this interval, *C. pygmaeus* presented its lowest  $\hat{\psi}$  value.

Site-specific species richness ranged from 3 to 7 species. We did not find a relation between altitude and

species richness (Additional file 5: Appendix S5), but the higher species richness values were estimated for low (800 m) and high (2500 m) levels of the altitudinal gradient (Fig. 4a). The number of site-specific species in the units where *A. ordinarius* was detected ( $\bar{x} = 6$  species (min–max=4–7)) did not differ from the units where it was undetected (5 species (3–7);  $\chi^2 = 3.02$ ,  $df = 58$ ,  $p = 0.08$ ). The accumulated value of the number of species for the set of units where *A. ordinarius* was detected (16 species) was similar to the set of units where it was undetected ( $\bar{x} = 16$  species (min–max=12–18);  $t = -1.64$ ,  $df = 99$ ,  $p = 0.10$ ). Finally, the site-specific number of species at risk was higher in sampling units where *A. ordinarius* was detected ( $\bar{x} = 3$  species (min–max=2–5)) than on units in which it was undetected (2 species (1–3);  $\chi^2 = 7.8$ ,  $df = 58$ ,  $p = 0.005$ ; Fig. 4b). The accumulated number of species at risk was higher for the set of units where *A. ordinarius* was detected (9 species) than in the set of units where it was undetected ( $\bar{x} = 7$  species (min–max=4–9);  $t = -17.26$ ,  $df = 99$ ,  $p < 0.001$ ).



Discussion

In northeastern Michoacán, the cropland proportion in the landscape was the most important variable explaining the distribution of diurnal amphibian assemblages in riparian zones, with distinct species responses. Air humidity did not represent a reliable predictor for the estimated detection probability. High values of amphibian richness were not restricted to riparian zones in a

particular altitudinal level. In sampling units occupied by *A. ordinarium*, we estimated greater number of species at risk. This result supports the consideration of *A. ordinarium* as a flagship species for amphibian conservation.

Potential amphibian diversity

Most amphibians are highly sensitive to high temperature and low environmental humidity, so they frequently



are more active at night or during the rainy season (Wells 2010). Despite the accuracy of our estimations of the number of potential species belonging to the metacommunity, they can only be suited for diurnal assemblages. Except for leopard frogs (11 *Lithobates* spp.) and *A. ordinarium*, the remaining riparian amphibians in the region are mainly active at night (35 species), so our model could have omitted most nocturnal species. Because of unsafety and logistic constraints (e.g., traveling time among sampling units and areas of difficult access), night visual encounter surveys represent a non-plausible alternative for estimating the amphibian richness in riparian zones. On the other hand, conducting pitfall traps setting (with daily checking) could be alternatives for assessing the assemblage dynamics of amphibians in riparian vegetation (e.g., Steelman and Dorcas 2010; Todd et al. 2009).

### Amphibian species detection

We obtained reliable estimations for the association between occupancy and landscape variables but not for the association of temperature and humidity with any amphibian detection probability. By general, temperature and humidity conditions have been recognized as important environmental variables determining different amphibian activities (e.g., movement, calling, even egg spawning; Kaefer et al. 2009; Steelman and Dorcas 2010; Ocock et al. 2014). In high temperature and low humidity conditions, to avoid the risk of desiccation risk, amphibians prefer to be inactive, hidden, or occupy higher vegetation strata (Steelman and Dorcas 2010; Sunday et al. 2014; Ocock et al. 2016). These behaviors could explain the estimated detection probabilities ( $\hat{p}$ ) < 0.1 for almost half of our species, even when our sampling design considered dry and rainy seasons. In this sense, one option to understand the role of these variables (air temperature and humidity) in the probability of detection is to sample the amphibians during the period of highest activity, such as afternoon and evening.

### Croplands as a predictive variable for species distribution

Compared to forest, land-use type (i.e., cropland or artificial pasture) present lower air humidity and a greater variability in environmental temperature (i.e., more extreme temperatures), representing hostile conditions for many amphibian species (Suazo-Ortuño et al. 2008; Díaz-García et al. 2017; Nowakowski et al. 2018). In addition, habitat transformation modifies the microclimatic conditions of forest patches, compromising their ability to preserve amphibian populations (Russildi et al. 2016; Arroyo-Rodríguez et al. 2017). Thus, assessing the response of species to land-use change is a fundamental step in the development of conservation strategies (Manton et al. 2019; Wagner et al. 2021).

Our results showed that amphibian species do not share similar responses to the proportion of cropland in the landscape. This pattern could be associated with species-specific environmental tolerance to temperature and humidity variations (Watling and Braga 2015; Meza-Parral et al. 2020). Salamanders of the Plethodontidae family and leaf litter frogs in the *Craugastor* and *Eleutherodactylus* genera frequently show low tolerance to high temperatures in modified habitats, which corresponds to the negative response of *Ishtmura bellii*, *Pseudoeurycea leprosa*, and leaf litter frogs to an increase in the proportion of cropland (Nowakowski et al. 2018; Meza-Parral et al. 2020). The negative response of most leaf litter frog species to increasing in the proportion of croplands in the landscape could also be a consequence of their cryptic coloration in forested areas, becoming more conspicuous in modified landscapes, compromising their survival (Delhey and Peters 2017).

In this study, the leopard frog *Lithobates neovolcanicus* and some tree frogs showed a positive response in occupancy probability with the increasing of cropland proportion. Similarly, in other studies some leopard and tree frogs have been recognized for their ability to inhabit modified environments, and their detection may be higher in these environments (e.g., Suazo-Ortuño et al. 2011; Díaz-García et al. 2017; Aguilar-López et al. 2020). For these frog species, their capacity for inhabiting modified landscapes has been linked to their tolerance to high temperatures (Tracy et al. 2008; Meza-Parral et al. 2020). Plethodontidae salamanders and leaf litter frogs need terrestrial environments with no extreme temperature and humidity conditions that could damage the spawn of their eggs and the development of their embryos (Haddad and Prado 2005; Siqueira et al. 2021). Leopard and tree frog reproduction, however, depends only on the availability of water bodies and therefore, their reproductive mode could represent an advantage in modified landscapes (Boissinot et al. 2015; Nowakowski et al. 2018).

We estimated high occupancy probabilities for different amphibian species in modified landscapes, and this pattern could have resulted from extrinsic factors such as crop type. Croplands with multiple agrochemical applications become harmful to numerous amphibian species, even those inhabiting nearby forested areas and water bodies (Ficetola et al. 2011; Guerra and Aráoz 2016). Among negative agrochemical effects on amphibian populations are low survival, decreased larvae growth, poor body condition, increased malformations, and parasite load (Rohr et al. 2008; Baker et al. 2013; Guerra and Aráoz 2016). On the other hand, rustic plantations that limit the use of agrochemicals (e.g., coffee and cacao) provide microhabitats for several amphibian species, even assemblages similar to pristine areas (Pineda and

Halffter 2004; Boissinot et al. 2015; Cervantes-López et al. 2022). In the study area, crops are seasonal and/or traditional, with no technification, where the agrochemicals are applied sporadically during the year. Consequently, our results showed that landscapes including rustic plantations could be less harmful to the populations of several amphibian species, even those at risk (i.e., *L. neovolcanicus* and *A. ordinarius*).

Identifying ecological thresholds that maintain the highest species richness and populations viability is a way to implement effective conservation plans and sustainable management practices (Johnson 2013; van der Hoek et al. 2015). We do not know if landscapes with a proportion of cropland higher than 45% could maintain viable populations of these amphibian species. Nevertheless, the assessment of amphibian populations in the face of land-use change requires a broader gradient of cropland cover. Furthermore, we suggest the conservation of at least 50% of the original vegetation coverage (including riparian vegetation) to preserve amphibian populations sensitive to land-use change.

#### Importance of riparian zones for amphibian conservation

Riparian vegetation is a very important landscape element that prevents soil erosion, water pollution, and disease propagation (Brouwer et al. 2011; Land et al. 2016; Mokondoko et al. 2016). Because many amphibians with aquatic larvae depend on water conditions to complete their life cycles, maintaining riparian vegetation is crucial for their conservation in modified landscapes (da Rocha et al. 2020; Piñon-Flores et al. 2021). For example, in Brazil the riparian forest zone was associated with a higher density of the Kurupi tree frog (*Boana curupi*) and spinythumb frog (*Crossodactylus schmidtii*) larvae and with a lower frequency of damage by agrochemicals and UV radiation than in streams in deforested zones (da Rocha et al. 2020). Even for *Ambystoma ordinarius*, a species tolerant to land-use change, the width of riparian vegetation was positively associated with abundance, better body condition, and lower malformation probability (Soto-Rojas et al. 2017; Piñon-Flores et al. 2021). Therefore, in northeastern Michoacán the incidence of amphibian species in modified landscapes (all with aquatic larvae) could be explained by the water bodies associated with the presence of riparian forest.

In a landscape context, the maintenance of genetic diversity within amphibian populations is a key element for species conservation (Frankham 2010). For amphibian populations, riparian vegetation has been recognized as optional routes for migration and dispersal where genetic variability is maintained (Richardson 2012; Arroyo et al. 2018). For instance, in Nigeria, populations of two threatened frogs (*Cardioglossa schioetzi*

and *Leptodactylodon bicolor*) present within riparian forest remnants have maintained genetic variability values similar to those present in continuous forest populations (Arroyo-Lambaer et al. 2018). Furthermore, for the spotted salamander (*Ambystoma maculatum*), a riparian zone has been fundamental in maintaining population connectivity in modified landscapes (Richardson 2012). Therefore, we believe that the protection of riparian vegetation is fundamental for amphibian conservation, especially in regions with a high proportion of land-use change such as northeastern Michoacán.

#### Potential of *Ambystoma ordinarius* as a flagship species

Flagship species can be used to protect whole ecosystems (Barua et al. 2011; Bowen-Jones and Entwistle 2002). For example, the "ajolote" (*Ambystoma mexicanum*) is a species at risk of extinction, but its popularity has allowed the protection of those species sharing the same habitat (Bride et al. 2008). Even though *A. ordinarius* shows a narrow distribution (21 localities), it maintains its populations in landscapes with a large proportion of cropland (Oropeza-Sánchez et al. 2021). Thus, *A. ordinarius*, is present in different assemblages since those from mature forest until the composed by disturbance-tolerant species. Therefore, to grant flagship species category to *A. ordinarius* could benefit the conservation of numerous amphibians and riparian zones. It is important to assess different diversity metrics (beta, functional or phylogenetic diversity) of amphibian assemblages in the region to evaluate this possibility.

Due to the estimation of the highest number of threatened species found in the sampling units occupied by *A. ordinarius* and a higher estimated richness of amphibians in upper and lower altitudes, strategies to protect these areas jointly are required. This conservation effort could benefit not only diurnal amphibian species, but also nocturnal ones. To achieve this goal, government programs such as paying for environmental services or micro-watershed restoration may be an option, at least while long-term actions are still not performed that include environmental education programs that ensure the conservation of amphibians and riparian vegetation in the region (CONAFOR 2020; Mokondoko et al. 2016).

#### Conclusion

Our results showed how the proportion of cropland in the landscape affects the patterns of diurnal amphibian richness in northeastern Michoacán. Not all amphibian species in the region were negatively affected by traditional croplands; consequently, this practice could be an option for sustainable land management with low harm to amphibians. We also found evidence that protecting the distribution area of *A. ordinarius* can be

advantageous in preserving other species at risk. The usefulness of considering *A. ordinarium* as a potential flagship species for conservation should be further evaluated by studies that consider other biodiversity facets such as beta, phylogenetic and functional diversity in sampling units inhabited by *A. ordinarium*. Finally, the riparian zones hold great amphibian species richness and connect their populations; thus, these zones should be considered for future landscape assessments and eventually for regional conservation plans.

### Abbreviations

IUCN: International Union for Conservation of Nature and Natural Resources; SEMARNAT: Ministry of Environment and Natural Resources; INEGI: National Institute of Statistics and Geography; MSOM: Multi-Species Occupancy Models; MCMC: Markov chain Monte Carlo; WAIC: Watanabe–Akaike Information Criterion; CI: Credibility intervals; EVS: Environmental Vulnerability Score.

### Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s13717-022-00408-7>.

**Additional file 1: Appendix S1.** Proportion of each land-use cover type on a 500 m radius for the 60 sampling units.

**Additional file 2: Appendix S2.** R Script to estimate multi species occupancy models, site-specific richness and draw figures.

**Additional file 3: Appendix S3.** Detection/no detection records for 20 amphibian species detected on riparian zones from Northwest Michoacán state.

**Additional file 4: Appendix S4.** Effect of each explaining variable on detection and occupancy probability of every amphibian species and the community on logit scale.

**Additional file 5: Appendix S5.** Coefficients of each variable in the models to explain occupancy of amphibians in riparian zones of Northwest Michoacán, Mexico.

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### Author contributions

All authors conceived the sampling design. MTOS conducted the sampling. RMS and MTOS interpreted data. MTOS wrote the manuscript. RMS, ISO and JBM revised the manuscript. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets used for the current study are available from the corresponding author upon reasonable request.

### Declarations

#### Ethics approval and consent to participate

The capture and handling of individuals were carried out in strict accordance with the guidelines for the use of live amphibians and reptiles in field research compiled by American Society of Ichthyologists and Herpetologists (ASIH).

#### Consent for publication

Not applicable.

#### Competing interests

The authors declare that they have no competing interests.

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