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"Heaven" of Data Deficient Species: The Conservation Status of the Endemic Amphibian Fauna of Vietnam

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Abstract: Predicting the true status of Data Deficient (DD) species is a prominent theme in recent conservation biology, but there still is much debate regarding the conservation approach that should be used for DD taxa and no definitive conclusions are yet available. We review and analyse the current data available on the conservation status of amphibians in Vietnam, with an emphasis on the DD species. We also compare Vietnamese DD frequency of occurrence with other regions of the world, examine the extent of the range of taxa divided by Red List status, and explore the protection attributes of the taxa based on their inclusion within protected areas of Vietnam. We documented that the analysis of amphibians in Southeast Asia, and especially in Vietnam, substantially agrees with patterns highlighted by previous global research, and confirms the risk that several DD species may silently go extinct without their actual risk ever being recognized. Importantly, our study showed that fine-scale analyses are essential to highlight the potential drivers of extinction risk for the DD species of amphibians. A crucial next step for conservation policies in Vietnam (and in surrounding countries) is developing and implementing species-specific studies targeted at addressing each species' drivers of extinction and determining science-based strategies for minimizing their extinction risk.

Keywords: amphibia; IUCN red list; risk assessment; global patterns

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1. Introduction

Amphibian populations have been declining for decades for many reasons, signalling a modern biodiversity crisis [1]. According to some authorities, this crisis may even be indicative of an ongoing mass extinction process [2–5]. In the IUCN Red List, approximately 35% of amphibian species (2606/7486) are threatened with extinction and another 15% (1145/7486) are listed as Data Deficient (DD) as scientists have insufficient information regarding their abundance and distribution [6].

Current mathematical models suggest that Data Deficient amphibians are more likely to face extinction than species with an assigned category (from Least Concern (LC) to Critically Endangered (CR); [7,8]), with these vertebrates facing even worse extinction risks than all the other taxa, aside from primates [9] and chelonians [10]. Moreover, the frequency of DD amphibian species is slightly higher than in reptiles (14.5%; 1487/10222) and mammals (14%; 839/5974), and much higher than in birds (0.41%; 46/11188) [6]. The discrepancy between amphibians and other vertebrates could be due to differences in geographic range, ecological guilds, life cycles, and reliance on multiple environments, with a limited distribution that makes the species more vulnerable to threats [11].

A biodiversity hotspot [12], Southeast Asia has one of the highest concentrations of endemic species in the world, including amphibians [13,14]. Despite this, data on

the ecology and distribution, and therefore on threats to the survival of many Southeast Asian amphibians, are scarce (e.g., [15,16]). Southeast Asia has been largely overlooked from wide-scale amphibian conservation research so far: for instance, an analysis showed that, from 732 scientific articles that included "amphibian" and "conservation" in 2009, only eight articles referenced Southeast Asian countries [15]. Although several additional studies have recently become available (e.g., [17–19]), this lack of interest in such research is especially concerning due to the high number of DD amphibian species in this region [6] that could be threatened with extinction without recognition by the scientific community.

Vietnam is one of the megadiverse countries in the Southeast Asia region. Habitat destruction is particularly aggressive in Vietnam [20], where about 66% of the territory was a primary forest until the mid-twentieth century [21]. With the current deforestation rate [22–24], 42% of Vietnam's biodiversity and three-quarters of its original forest are projected to be lost by 2100 due to deforestation [25]. Vietnamese amphibians are characterized by a high level of species richness and local endemism as well as a high rate of new discoveries, but they are heavily threatened by forest loss [15] and by over-harvesting from the wild for consumption, traditional medicine, and the pet trade [26]. Climate change can also affect amphibians by increasing the risk of wetland reduction and disappearance (e.g., [27,28]). Despite this, according to [19], only 8% of threatened amphibian taxa and 3% of Vietnam's endemic amphibian taxa are currently kept in zoos worldwide.

In this paper, we review and analyse the current available data on the conservation status of amphibians in Vietnam, emphasising the DD species and the measures to be taken to manage this likely threatened category. In detail, (i) we represented the conservation status of Vietnamese amphibian species and compared them with those from around the world. Since the proportion of DD species in a selected area could be considered a proxy of the level of knowledge of a given taxon, (ii) we compared the frequency of occurrence of Vietnamese DD with those from other regions of the world to estimate whether amphibians are as studied in Vietnam as in other world regions. (iii) We examined which factors most threaten amphibians in Vietnam and worldwide. Moreover, (iv) we tested how the extent of the range of species, the level of protection of the taxa (i.e., the occurrence in protected areas), and the biogeographic status (endemic vs. non-endemic) vary across the IUCN categories. Furthermore, in our study, we also considered the Not Assessed (NA) amphibian species, which are not present in the IUCN list, to increase the exhaustiveness of our analysis of poorly known Vietnamese species. Our study would therefore represent a comprehensive synopsis of the largest online databases from which we highlighted the threats and conservation status of Vietnamese amphibians and the similarities and differences, in terms of threat assessment, with neighbouring countries in Southeast Asia and elsewhere.

2. Materials and Methods

2.1. Protocol

The IUCN Red List website (www.iucnredlist.org, accessed on 22 January 2023) was extensively searched and information on species distribution, risk extinction category, and Extent of Occurrence (EOO) were extracted. The IUCN Red List database was interrogated by applying the following search filters: Taxonomy = Amphibia; Red List Category = CR Critically Endangered, EN Endangered, VU Vulnerable, DD Data Deficient; Land Regions = Vietnam. To obtain a more comprehensive list of species endemic to Vietnam (i.e., including those not assessed by IUCN), we searched the Amphibiaweb website (https://amphibiaweb.org, accessed on 19 January 2023) by selecting the option "occurring in" and "endemic to" in the search field "Country". All the species listed as endemic to Vietnam on the Amphibiaweb website were checked on the Amphibian Species of the World website (6.1; Frost and the American Museum of Natural History 1998–2021; https://amphibiansoftheworld.amnh.org, accessed on 19 January 2023) by consulting the original publications listed therein to gather detailed information on the distribution at the fine-scale level and recent taxonomical revisions not yet updated on the Red List website.

All species occurring in Vietnam and at least one other country (also those with uncertain occurrence outside Vietnam) were considered sub-endemic. These species were excluded from all analyses except those on biogeographic status.

2.2. Statistical Analyses

To depict the overall Vietnamese amphibian conservation status and that of endemic taxa, we built a χ^2 contingency tables test to explore (i) the frequency differences between the total number of Vietnamese species dataset and the Vietnamese endemic species dataset concerning their distribution across the various threatened categories (CR, EN, VU) [6], as well as the (ii) frequency differences between Vietnamese endemic species and world amphibians for frequencies of IUCN [6] categories (CR, EN, VU, DD, NT, LC).

We do not know in which IUCN category the currently DD species will be placed once sufficient information will be available, but it is possible to calculate the projections by using the criteria proposed by IUCN [29]:

(i) "Mid-point" (DD species have the same fraction of threatened species as data sufficient species: VU + EN + CR/assessed-DD);
(ii) "Lower bound" (none of the DD species is threatened: VU + EN + CR/assessed;
(iii) "Upper bound" (the most pessimistic estimate of extinction risk where all of the DD species are threatened: VU + EN + CR + DD/assessed);
(iv) "Species elevated conservation concern" (DD species have the same fraction of threatened species and Near Threatened species are evaluated as DD species).

These projections were made for both Vietnamese and global amphibians.

To test how the number of endemic amphibian species assigned to the DD or Not Assessed (NA) categories varies according to the geographical regions in which they are located, we carried out three non-parametric Kruskal–Wallis tests (K–W test). The proportions of DD, NA, and DD + NA on total assessed species were used as dependent variables, while the geographic regions were selected as predictors. The geographical regions considered are: Neotropics (Brazil, Perú, Ecuador, Bolivia, Chile, Colombia, Venezuela, and Argentina), Central America (Mexico, Guatemala, Honduras, Panama, Costa Rica, and Cuba), East Africa (Kenya and Tanzania), Madagascar, Southeast Asia (India, Japan, and China), Australia, USA, and Asia (India, Japan, and China).

To understand whether and how Vietnamese species are threatened by different factors compared to amphibians worldwide, we used log-linear analysis on the frequencies of taxa among distinct threat typologies affecting overall amphibians (i.e., those considered by IUCN). We have created five macro-categories, representing a homogeneous group of threats, using the threat typology reported by the IUCN Red List:

(1) Urbanization (Residential and commercial development + Pollution);
(2) Natural resource use (Agriculture and aquaculture + Biological resource use);
(3) Industrial development (Energy production and mining + Transportation and service corridors);
(4) Alien species and disease;
(5) Climate change.

Those categories poorly represented in Vietnam were discarded (Human intrusions and disturbance; Natural system modifications; Geological events). We built a $5 \times 2 \times 4$ frequency table with frequencies of amphibian species as the dependent variable and threats (five levels: see above), area (two levels: World vs. Vietnam), and risk category (four levels: CR, EN, VU, DD) as categorical predictors. We analysed such a multi-way frequency table for an appropriate model through simultaneously testing for all k-factor interactions (all 2-way and 3-way) and all marginal and partial association models.

We tested how the distribution extent of threatened Vietnamese amphibian species varies among the IUCN extinction risk categories, depending on biogeographic status (endemic vs. sub-endemic) and the implementation or non-implementation of conservation actions, indicated on the IUCN website as "Occurs in at least one protected area: Yes/No".

Therefore, we built a General Linear Model (GLM: identity link function) with species range area (EOO; km^2) as the response variable (normal distribution), and IUCN category, biogeographic status, and the occurrence in at least one protected area as categorical factors. All tests were performed using R software (version 4.2.1, R Core Team), except log-linear analyses for which Statistica software (Statsoft, v. 8.0) was used with alpha set at 5%. Means are followed by ±1 Standard Deviation.

3. Results and Discussion

3.1. Amphibian Diversity and Conservation Status in Vietnam

There were some discrepancies across the consulted databases in the number of taxa occurring in Vietnam: according to the Amphibiaweb database (https://amphibiaweb.org/, accessed on 19 January 2023), there were 274 species (261 frogs, 10 salamanders, and three cecilians), with 18 endemic species lacking IUCN assessment (Supplementary Table S1). According to IUCN [6], there were 278 assessed taxa distributed among risk categories as follows: DD = 35, LC = 153, NT = 8, VU = 33, EN = 46, and CR = 3. These numbers differ slightly from what was reported just in 2021 (275 taxa, 33 DD species) [19] based on the same sources, and this is due to the continuing revision/discovery of new taxa in this area. According to the Amphibiaweb and IUCN Red List databases, 122 and 77 species were endemic to Vietnam, respectively (Table S2). After checking for taxonomic revision and updated ranges, we recorded 93 endemic (95 reported in [19]) and 32 sub-endemic amphibian species from the pooled databases (Table S3), distributed along the IUCN risk categories as follows: DD = 24, LC = 23, NT = 3, VU = 17, EN = 38, CR = 2, and NA = 18. From the contingency table containing the number of endemic/sub-endemic and non-endemic Vietnamese species, no significant differences concerning their distribution across the IUCN threatened categories were observed (χ^2 test; df = 2; $p = 0.4$), with the frequency of CR, EN, and VU species being very similar (Vietnam: CR = 3.7%, EN = 51.6%, VU = 40.2%; Endemic: CR = 3.5%, EN = 66.7%, VU = 29.8%). According to the IUCN Red List, Vietnam also hosts a considerably higher number of endemic/sub-endemic species (E: N = 77/278, that is 27.7%) than surrounding Laos (E: N = 20/166, 12%) and Cambodia (E: N = 17/94, 18%). Furthermore, the ratio between threatened and total endemic species also seems to be higher (ET: N = 47/82, 57.3%) than in Laos (ET: N = 8/23, 34.8%) but not Cambodia (ET: N = 8/10, 80%). However, Cambodia hosts a considerably lower number of endemic species and the higher proportion of species at risk could be biased.

The comparison of the threatened species' frequencies between species endemic to Vietnam and world amphibians revealed an uneven distribution of extinction risk categories ($p < 0.001$ at χ^2 test), with a higher proportion of VU, EN, and DD taxa for species endemic to Vietnam compared to world amphibians, whereas the opposite was true for CR, NT, and LC taxa (Figure 1).

We calculated the frequency of "threatened species" and "species of elevated conservation concern", in other words, the likely proportion of threatened species estimated using the criteria proposed by IUCN [29] which also considers species currently labelled as DD. Vietnamese amphibians showed a remarkably higher proportion of threatened taxa irrespective of the calculation (i.e., mid-point and lower-upper bounds values) than world species (Figure 2). Thus, Vietnam's proportion of threatened species outnumbered that estimated for world amphibians, and the proportion of species of elevated conservation concern was consistently much higher for Vietnam than for the rest of the world (Figure 2).

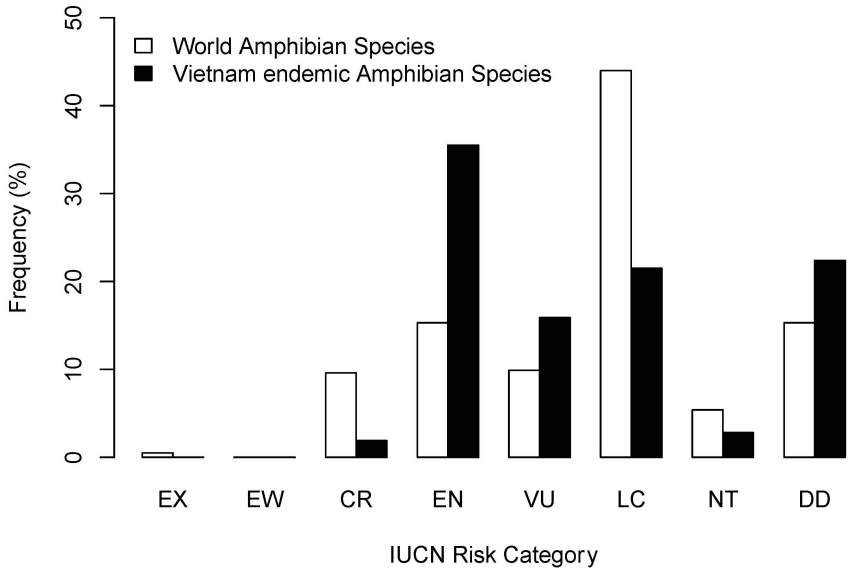


Figure 1. Distribution of IUCN extinction risk categories [6] in the world's amphibian species versus endemic Vietnamese amphibian species. Symbols: EX = Extinct; EW = Extinct in the wild; CR = Critically Endangered; EN = Endangered; VU = Vulnerable; LC = Least Concern; NT = Near Threatened; DD = Data Deficient.

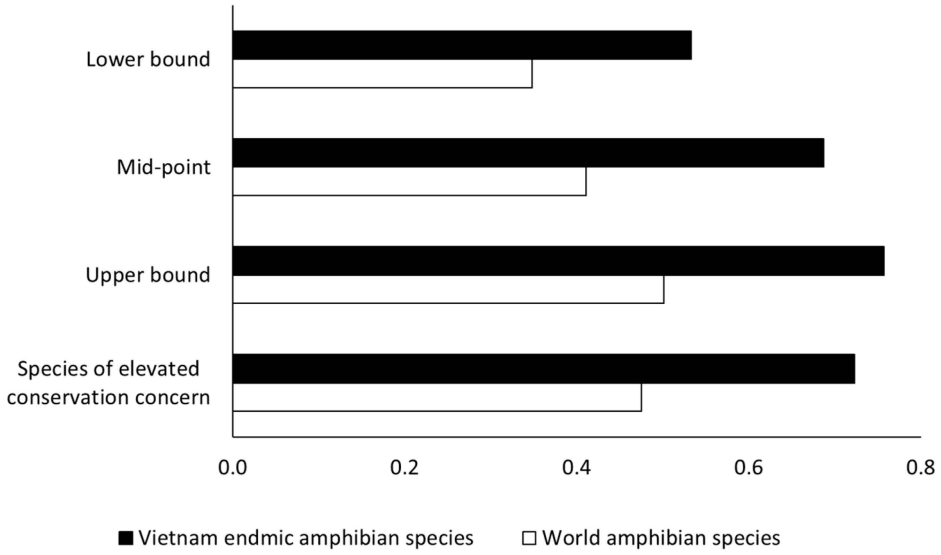
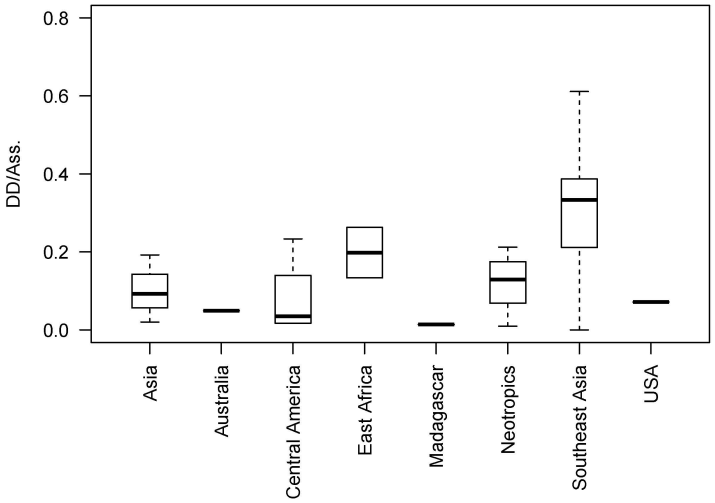


Figure 2. The proportion of threatened species (lower bound, mid-point, and upper bound values [29]); and proportion of species of elevated conservation concern calculated for Vietnam and world amphibians.

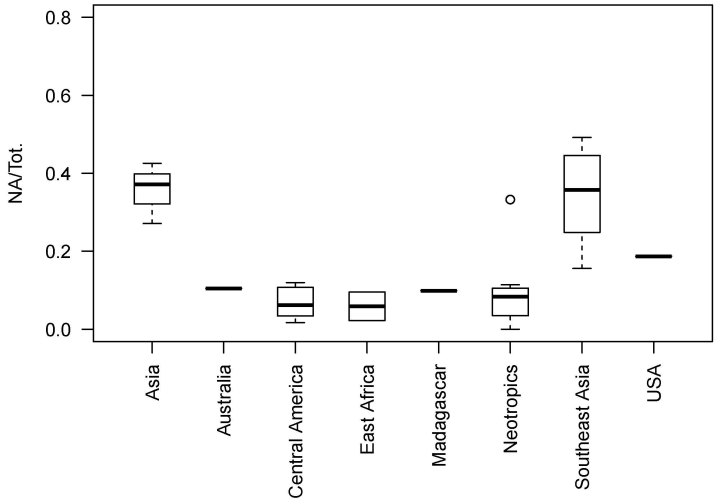
3.2. Vietnam vs. Other Geographical Regions

Currently, 15.3% of all the IUCN-assessed amphibian species [6] are assigned to the DD risk category (22% in [30]) and are unevenly distributed worldwide, with just 0.4% of the world area hosting more than 80% of DD amphibians [30]. Those areas are in the Neotropics, East Africa, Madagascar, and Southeast Asia. The proportion of DD species on the total IUCN-assessed amphibians greatly varied across world areas, being higher in Southeast Asia compared to the other world areas, although the observed differences were not statistically significant (K–W test: $H_{7,29} = 9.127$; $p = 0.244$; Figure 3A). The percentage of NA species was also higher in Asia and Southeast Asia than in the remaining world regions (K–W test: $H_{7,29} = 19.096$; $p = 0.008$; Figure 3B). When DD and not assessed (NA) species were considered together, Southeast Asia showed the highest proportions (K–W

test: $H_{7,29} = 18.80$; $p = 0.009$; Figure 3C). The contribution of NA and DD taxa to Southeast Asia species lacking risk category assessments, especially to Vietnamese batrachofauna (probably the highest among countries worldwide: 43%; 24 DD and 18 NA; Table S4), is considerable. Taxonomic instability may be one of the reasons for the high number of NA and DD species in these regions, given that new species of amphibians, often produced by the splitting of previously known "species complexes", are described at a higher rate than for other vertebrates, with potential inflation of narrow-range species [31]. However, taxonomic inflation seems not to bias amphibian diversity [32], especially in areas rich in cryptic species like Southeast Asia and Madagascar [13,32,33], while this may be true for other vertebrate groups such as primates and birds [31]. Additionally, the life-history traits of amphibians also contribute to their susceptibility to the presumed current mass extinction [34]. Amphibians often exhibit not only small geographic ranges but also a high degree of habitat specialization, particularly in tropical and subtropical regions [35]. Moreover, amphibian megadiversity concentrates in poorly or unexplored regions of the planet (i.e., the Neotropics and Southeast Asia) and it is logical to assume that high levels of undocumented diversity (i.e., species occurrence and uncertainty in their fine-scale distribution) correlate to low levels of knowledge of species extinction risk, thus leading to a higher rate of DD species [8,30].

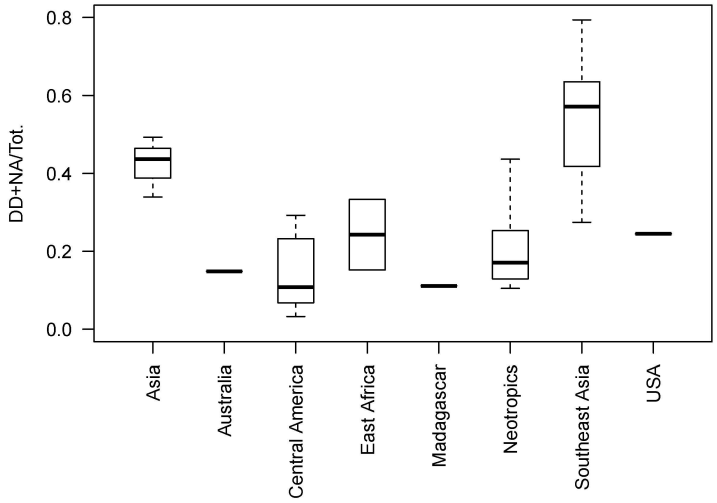


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Proportions of Data Deficient (DD; (**a**)), Not Assessed (NA; (**b**)), and Data Deficient+Not Assessed (DD+NA; (**c**)) amphibian species compared to the total endemic amphibians across world regions. For the composition of world regions, refer to Table S4. Spreads represent minimum and maximum values; the box reports the 1st and 3rd quartiles, the bar indicates the median and the circle represent the outliers.

The scientific community should ponder on the importance of giving more attention and dedicating more research funds to these poorly studied regions [36], thus attempting to reduce the knowledge shortfalls which represent a major issue for amphibian conservation [7]. Among the priority research areas indicated by [30], those from Southeast Asia are mostly covered by intensive crops or undergoing high deforestation rates [37]. In such areas with high human pressure, we need information on species distributions at the highest spatial resolution to evaluate both global and local factors undermining the persistence of most DD species. Therefore, a closer inspection of the endemic and sub-endemic taxa categorized as DD is needed to assess whether and which factors are driving those species to extinction. This analysis of Vietnamese DD species revealed that their range extent was extremely narrow and often limited to 1–3 points locations (Table S5). That is, 87.5% (n = 21) of the DD species are known from just the type locality (for example, *Megophrys minuta*, *Microhyla pulverata*) or a few more point locations (Table 1), and 25% of them do not occur in a protected area. For one species (*Microhyla picta*), the locality of capture is yet unknown. The mean range of DD species was 3761 ± 8636 km^2 (sample size, n = 24).

Table 1. List of threatened and Data Deficient endemic and sub-endemic species of amphibians of Vietnam. For each species, the IUCN extinction risk category, the biogeographic status (endemic or sub-endemic), the number of known locations (1–3, > 3 = several), the area of extent range (Extent of Occurrence, EOO), and level of protection (whether the species range falls at least in part in protected areas) are shown. As for the sub-endemic taxa, the range can extend to China ([a]), Laos ([b]), or Cambodia ([c]).

Species	IUCN	Status	N Locations	Area (km^2)	Protected Area
Leptobrachella botsfordi	CR	Endemic	1	36	Yes
Leptobrachella rowleyae	CR	Endemic	1	19	Yes
Amolops cucae	EN	Endemic	1	2321	Unknown
Amolops minutus	EN	Subendemic [a]	several	2383	Unknown
Amolops ottorum	EN	Subendemic [a]	3	2985	Yes
Gracixalus lumarius	EN	Endemic	1	425.6	Yes
Gracixalus nonggangensis	EN	Subendemic [a]	several	2317	Yes

Table 1. *Cont.*

Species	IUCN	Status	N Locations	Area (km^2)	Protected Area
Gracixalus sapaensis	EN	Subendemic [a]	several	1947	Yes
Hylarana montivaga	EN	Endemic	several	3139	Unknown
Kalophrynus cryptophonus	EN	Endemic	2	5438	Yes
Kurixalus viridescens	EN	Endemic	3	355	Yes
Leptobrachella applebyi	EN	Endemic	2	244.85	Yes
Leptobrachella ardens	EN	Endemic	3	598	Yes
Leptobrachella bidoupensis	EN	Endemic	3	214.03	Yes
Leptobrachella firthi	EN	Endemic	1	3920	Yes
Leptobrachella kalonensis	EN	Endemic	3	1472	No
Leptobrachella macrops	EN	Endemic	2	491	No
Leptobrachella maculosa	EN	Endemic	3	616	Yes
Leptobrachella namdongensis	EN	Endemic	3	271	Yes
Leptobrachella pallida	EN	Endemic	3	142	Yes
Leptobrachella pluvialis	EN	Endemic	3	2597	Yes
Leptobrachella pyrrhops	EN	Endemic	2	239	No
Leptobrachella tadungensis	EN	Endemic	3	640	Yes
Leptobrachium ngoclinhense	EN	Endemic	2	2912	Yes
Leptobrachium xanthospilum	EN	Endemic	3	4379	Yes
Liuixalus calcarius	EN	Endemic	3	1207	Yes
Megophrys fansipanensis	EN	Subendemic [a]	1	629	Yes
Megophrys gerti	EN	Endemic	3	4303	Yes
Megophrys hoanglienensis	EN	Subendemic [a]	several	3213	Yes
Micryletta nigromaculata	EN	Endemic	2	3206	Yes
Nanohyla pulchella	EN	Endemic	several	3901	Yes
Odorrana yentuensis	EN	Endemic	1	2495	Yes
Oreolalax sterlingae	EN	Endemic	3	639	Yes
Philautus catbaensis	EN	Endemic	3	198	Yes
Rhacophorus calcaneus	EN	Endemic	several	4138	Yes
Rhacophorus helenae	EN	Endemic	several	4735	Yes
Rhacophorus vampyrus	EN	Endemic	2	2082.5	Yes
Theloderma nebulosum	EN	Endemic	1	940.12	Yes
Theloderma palliatum	EN	Endemic	1	1443.43	Yes
Theloderma ryabovi	EN	Endemic	2	2736	No
Amolops splendissimus	VU	Endemic	several	8573	Unknown
Gracixalus quyeti	VU	Subendemic [b]	several	7406	Yes
Kalophrynus honbaensis	VU	Endemic	1	14	Yes
Kurixalus motokawai	VU	Subendemic [b]	several	11,350	Yes
Leptobrachella bourreti	VU	Subendemic [a]	several	15,330	Yes
Leptobrachium leucops	VU	Endemic	several	7617.07	Yes
Limnonectes quangninhensis	VU	Subendemic [a]	several	15,169.5	Yes
Microhyla pineticola	VU	Endemic	1	11,908	Yes
Nanohyla annamensis	VU	Endemic	several	9889	Yes
Nanohyla arboricola	VU	Endemic	1	7964	Yes
Quasipaa acanthophora	VU	Subendemic [a]	2	7310	Yes
Raorchestes gryllus	VU	Endemic	2	6562	Yes
Rhacophorus marmoridorsum	VU	Endemic	2	6927	Unknown
Rhacophorus vanbanicus	VU	Subendemic [a]	several	19,653	No
Theloderma auratum	VU	Subendemic [b]	several	19,292	Yes
Tylototriton vietnamensis	VU	Subendemic [a]	several	6639	Yes
Tylototriton ziegleri	VU	Endemic	1	16,218	Yes
Amolops iriodes	DD	Subendemic [a]	1	649	Yes
Ichthyophis catlocensis	DD	Subendemic [c]	1	730	Yes
Ichthyophis chaloensis	DD	Subendemic [b]	1	2042	Yes
Kurixalus gracilloides	DD	Endemic	1	14	Yes
Leptobrachella crocea	DD	Endemic	1	135.35	Yes
Leptobrachella nahangensis	DD	Endemic	1	Unknown	Yes
Leptobrachella nyx	DD	Subendemic [a]	3	2096	Yes

Table 1. *Cont.*

Species	IUCN	Status	N Locations	Area (km^2)	Protected Area
Megophrys caobangensis	DD	Subendemic [a]	1	41	Yes
Microhyla aurantiventris	DD	Endemic	1	142	Unknown
Microhyla darevskii	DD	Subendemic [b]	1	1156	No
Microhyla minuta	DD	Endemic	1	Unknown	Yes
Microhyla picta	DD	Endemic	2	Unknown	Unknown
Microhyla pulverata	DD	Endemic	1	Unknown	Unknown
Nanohyla nanapollexa	DD	Subendemic [b]	2	2658	Yes
Odorrana mutschmanni	DD	Subendemic [a]	1	Unknown	No
Philautus maosonensis	DD	Subendemic [a]	2	20,270	Yes
Rhacophorus hoabinhensis	DD	Endemic	1	136	Yes
Rhacophorus larissae	DD	Subendemic [a]	1	Unknown	Yes
Rhacophorus viridimaculatus	DD	Subendemic [a]	1	Unknown	Yes
Theloderma annae	DD	Endemic	2	2022	Yes
Tylototriton pasmansi	DD	Endemic	1	31,636	Yes
Tylototriton sparreboomi	DD	Endemic	1	85	No
Vietnamophryne inexpectata	DD	Endemic	1	45	Yes
Vietnamophryne orlovi	DD	Endemic	1	75	Yes

As for VU species (n = 17), 52.94% are endemic to Vietnam, 29.41% are sub-endemic occurring also in China, and 17.65% are subendemic occurring also in Laos (Table 1). Their mean range area was 10,460 ± 5203 km^2 and 82.4% of them also occur in at least one protected area. For EN species (n = 38), 84.21% are endemic to Vietnam and 15.79% are subendemic occurring also in China. Their mean range area was 1998 ± 1542 km^2 and 81.6% of them occur in at least one protected area. As for the CR risk category, there are only two species (*Leptobrachella botsfordi* and *Leptobrachella rowleyae*), both endemic to Vietnam and both occurring in protected areas, with a mean species range of 27.5 km^2.

3.3. Analysis of Threats

As for the log-linear analysis of the threats, the least complex model that fitted the observed frequency table contained no three-way associations but included all two-way associations (Tables S6 and S7). The data from the log-linear analysis was used to calculate the percentage of Vietnamese vs. world and DD vs. threatened amphibian species subjected to each threat category. The results of the analysis suggested that the Vietnamese species are proportionally more threatened than that from the world by Natural resource use (+21%) and Industrial development (+4%), and less threatened by Climate change (−2%), Alien species and diseases (−14%), and Urbanization (−8%) (Table S8; the percentages indicate the delta between the percentage in Vietnam and the world used as a reference; positive values indicate a higher proportion in Vietnam with respect to the world and vice versa). Data Deficient species were threatened more by Natural resource use (+7%) and Alien species and diseases (+4%), and less by Urbanization (−3%), Industrial development (−2%), and Climate change (−5%) compared to the average of the other risk categories (Table S8; the percentages indicate the difference between the percentage of DD species and those in the other risk categories taken as a reference). The threat dynamics were therefore very different among regions, with the potential pressure of alien species being negligible in Vietnam compared to the world's general situation. We speculate that the megadiverse characteristics of the Vietnamese amphibian communities, including an exceedingly high species-specific micro-niche saturation, would have represented a functional filter against the ecosystemic permeability towards invasive species. The excess of threats from agricultural, aquacultural, and energy production practices in Vietnamese species is likely derived from the intensive landscape use planned in the country's economic exploitation programmes [38]. Interestingly, climate change had the opposite effect on threatened versus DD species, but we do not have sufficient information to stress firm conclusions on this discrepancy, especially because the two groups were consistent in terms of the overall

effects of the other threat categories. This fact further amplifies the immediate need for a more thorough evaluation of DD species using ad hoc field surveys aimed at collecting environmental and climatic data related to fine-scale species' distributions.

3.4. Amphibian Extinction Risk Categories and Biogeographic Status

The species' extent of distribution area (EOO) differs between IUCN Red List categories and according to biogeographic status (endemic vs. sub-endemic). However, the species range does not seem to vary between biogeographic status groups if it falls at least partly in protected areas (Table 2).

Table 2. Effect of extinction risk category (IUCN), biogeographic status (Status: endemic vs. sub-endemic), and inclusion in protected areas on the extent of distribution range (EOO) in threatened and Data Deficient amphibians from Vietnam.

Effect	*df*	Sum Sq	Mean Sq	F Value	Pr (>F)
Status	1	1.67×10^8	1.7×10^8	6.66	0.012
Protected Area	2	2.47×10^6	1,235,188	0.049	0.952
IUCN	3	7.53×10^8	2.5×10^8	10.013	1.55×10^{-5}
Residuals	67	1.68×10^9	2.5×10^7		

Overall, VU Vietnamese species exhibited larger EOO than EN, CR, and DD species ($p < 0.001$; Figure 4A). Interestingly, DD species show an EOO comparable to EN taxa, possibly supporting the consideration of DD species as being at high risk of extinction. Regarding biogeographic status, as expected, the wider the range of the species, the higher the probability that the species belongs to the sub-endemic group (Figure 4B). These patterns are entirely consistent with a priori expectations based on other groups studied elsewhere. Our main findings revealed that the conservation status of the amphibians of Vietnam is poorly known, with a remarkable portion of the assessed taxa being categorized as DD. The relative paucity of data on the distribution, biology, ecology, demography, and threats of so many amphibian species stands in stark contrast to the extremely fast habitat alteration and loss rates in Southeast Asia, especially in Vietnam. Although there is no consensus on whether DD species should be considered at risk [39,40], in the case of Vietnam, we can anticipate that a considerable amount of DD endemic species are likely to be threatened since the frequency of threatened species is higher among endemic than non-endemic species. Hence, the same pattern should be expected once the current endemic DD species are fully evaluated.

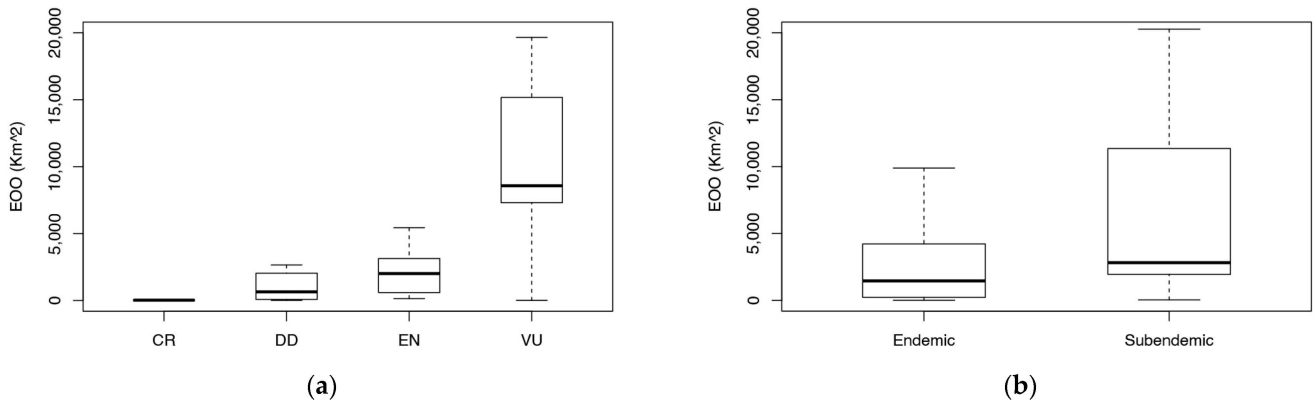


Figure 4. Effect of IUCN extinction risk category (**a**) and the biogeographic status (**b**) on the extent of distribution range in threatened and Data Deficient amphibians from Vietnam. Spreads represent minimum and maximum values; the box reports the 1st and 3rd quartiles, and the bar indicates the median.

The range extent of >90% of DD Vietnamese amphibian endemic species is represented by just a single forest point (i.e., the type locality) or a few locations in a very fragmented landscape, where forests are patchily interspersed within a matrix of plantations, especially at the lower elevations. For most species, IUCN Red List maps show distribution on a broad scale, and therefore no reliable information on the habitat occupied by species can be derived. However, for those species known from a single or a few locations (i.e., at the site level), IUCN maps represent a good indication of the exact locations where the species can be found and could provide reliable information on the habitat hosting the species. However, for a single or a few point locations, IUCN recommends verifying habitat information through site surveys [29].

Vietnam also hosts a considerably higher number of threatened endemic amphibian species (N = 47) than surrounding Laos (n = 8) and Cambodia (n = 8), see Table S2. This is due to the fact (1) that Laos and Cambodia are far less studied [41] and also because of (2) the "empty forest syndrome" [42]. Indeed, because of the extreme overhunting [42], the animal resources of forests in Laos and Cambodia appear to be heavily depleted even inside the protected primary forests [36,43]. In addition, indigenous biodiversity research is poorly developed in both these countries, with a considerable body of literature being produced by Vietnamese scientists [44]. Considering the high number of DD and NA amphibian species (34%), we can assume that the overall true conservation status of Vietnamese endemic species may be worse than estimated, especially in the northern territories bordering China and along the Central Highlands bordering Laos. Hence, we recommend an urgent investigation of data-poor species to acquire new information on the real range extension and population estimate in at least a few sites to quantitatively evaluate the main threats that the various populations are suffering at the local scale.

4. Conclusions

Our study documents that the diversity and risk status of Southeast Asia amphibians, and especially of Vietnam, substantially mirrors the patterns highlighted by [8] at the global scale and confirms the high chance that several DD species may silently go extinct without their actual risk ever being recognized [7]. Regarding the conservation of Vietnam's batrachofauna, the problem of data scarcity is exacerbated by the growing description of diversity in local taxa, so it would be beneficial to include both genetic and molecular analyses as well as morphological data to identify twin species [41]. More generally, a vast underestimation of species richness and endemism is expected in tropical areas [45].

This study demonstrates that fine-scale analyses can be crucial in highlighting potential extinction risk factors, especially for DD amphibian species whose known distribution is often punctiform or extremely spatially restricted. Therefore, an important next step for herpetofauna conservation policies in Vietnam (and surrounding countries) would be to develop and implement DD species-specific ecological studies aimed at highlighting different species-specific extinction risk factors and implementing science-based mitigation strategies to reduce extinction risk.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d15070872/s1, Supplementary materials (Tables S1–S8). Table S1. List of the amphibians of Vietnam, based on the Amphibia Web (https://amphibiaweb.org/) database (accessed on 19 January 2023). Table S2. Endemic species of amphibians of Vietnam and comparison with two other countries from South-East Asia, Laos, and Cambodia. For each species, the IUCN (2018) redlist status is indicated. The species shared by the three countries are in bold. Data from the IUCN Red List database of threatened species (https://www.iucnredlist.org/; accessed on 22 January 2023). Table S3. List of the amphibian species of Vietnam with their IUCN red list status (https://www.iucnredlist.org/; accessed on 22 January 2023). Table S4. Proportion of Data Deficient (DD) and Not Assessed (NA) species on the total endemic species in different world areas. Each world area is presented as follow: Neotropics (Brazil, Perù, Ecuador, Bolivia, Chile, Colombia, Venezuela, Argentina); Central America (Mexico, Guatemala, Honduras, Panama, Costa Rica, Cuba); East Africa (Kenya, Tanzania); Asia (China, India, Japan); Southeast Asia (Cambodia, Indonesia, Laos, Malaysia,

Myanmar, Thailand, Vietnam). Table S5. Data Deficient (DD) and not assessed (NA) species endemic and subendemic to Vietnam. For each species, the status (endemic or subendemic), the number of known locations, the range extension (i.e., the type and the extension of the locations), and the range description are reported (IUCN 2022). The range extension is classified as "small" if the locations are smaller than 1000 km^2, whereas it is classified as "medium" if the polygon representing the species' range is smaller than 5000 km^2, and it is classified as "large" if the polygon is larger than 5000 km^2. Table S6. Log-Linear analysis. Simultaneous test of all k-factor interactions. The improvement in fit when including all 2-way interactions in the model (K-Factor = 2) is highly significant (i.e., the model provides a very poor fit). The improvement in fit when adding all 3-way interactions to the model (K-Factor = 3) is not significant (i.e., the model provides an adequate fit). The least complex model that will fit the observed data should not contain any three-way associations but contains one or more two-way associations. N-Factors numbers represent no interaction (1), 2-way interactions (2), and 3-way interactions (3) among the considered factors (THREAT, AREA, and RISK CAT). Table S7. Log-Linear analysis. Tests of all marginal and partial associations. Table S8. Log-Linear analysis. Marginal tables of two-way associations. Threats are numbered as follows: (1) Urbanization (Residential & commercial development + Pollution), (2) Natural resource use (Agriculture & aquaculture + Biological resource use), (3) Industrial development (Energy production & mining + Transportation & service corridors), (4) Alien species and disease, and (5) Climate change. Data are showed as species frequencies. References [46–87] are cited in the Supplementary Material file.

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