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Species diversity and distribution of amphibians and reptiles in Sardinia, Italy

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Abstract. Although distribution databases are a dynamic tool, continuously updated, it is important to take "snapshots" of the species distribution over time to promptly identify potential conservation issues. With this work, we provide an update of the distribution of amphibians and reptiles in Sardinia and satellite islands. Data derive from both direct field observations (carried out since 2005 until July 2022) and literature, accounting for over 7000 records: 1416 records of 11 species of amphibians and 5600 records of 18 species of reptiles. Distribution maps (on 10 × 10 km UTM grid) of 29 species are provided in supplementary materials as well as the updated list of the amphibians and reptiles occurring in the circum-Sardinian islands. Most of the meshes were characterized by the presence of 1-3 amphibian species (73%) and 6-8 or 9-11 reptile species (32% with 6-8 species, 30% with 9-11 species). Species abundance was favoured by environmental heterogeneity, and mostly varied in relation to elevation range and edge density.

Keywords. Sardinia, amphibians, reptiles, islands, endemics, micro-insular herpetofauna, distribution maps.

INTRODUCTION

Sardinia is the second-largest island in the Mediterranean and, together with Corsica, with which it shares its paleo-origin, it is one of the most relevant biodiversity hotspots in the Mediterranean (Blondel et al., 2010).

Due to its long isolation (24-20 Mya), the complex geological history, the geographical position, the climatic and historical events, Sardinia is home to numerous endemic herpetological species, eight amphibians and five reptiles, some of which derive from ancestors present on the Sardinian-Corsican microplate before its detachment from the main European plate (Alvarez, 1972; Lanza, 1983; Carmignani et al., 1995, 2001, 2016; Corti et al., 1999; Speranza et al., 2002; Rodríguez et al., 2017). Sardinia is home to 11 amphibian and 18 reptile species (SHI, 1996; Bassu et al., 2010). The current herpetological composition of the Island can be mainly referred to a) the Messinian salinity crisis which occurred in the Miocene (~5 Mya) when important climatic variations occurred with consequent impact on flora and fauna, b) sea level oscillations due to the alternation of recurrent glacial and interglacial periods that have repeatedly separated and connected the island with Corsica and with the continent, c) the arrival of man (Corti et al., 1999; Duggen et al., 2003; Senczuk et al., 2019).

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as part of the atlas project of the Italian Society of Herpetology, SHI, 1996) preliminary distribution maps of the Sardinian species were reproduced, subsequently published with some updates in the "Atlas of Italian amphibians and reptiles" (Sindaco et al., 2006). In the last three decades, the scientific interest in Sardinian herpetological species has intensified. In addition to some updates on the species distribution, an increasing number of articles have been produced focusing on phylogeography, ecology and conservation which have also contributed to provide data on the distribution of amphibians and reptiles on the Island (Corti et al., 2000, 2010; Vasconcelos et al., 2006; Van der Meijden et al., 2009; Salvi et al., 2010, 2011, 2017; Salvi and Bombi, 2010; Vamberger et al., 2011; De Pous et al, 2012; Fritz et al., 2012; Bombi and Vignoli, 2014; Biaggini et al., 2016; Rodríguez et al., 2017; Cossu et al., 2018; Ficetola et al., 2018; Lunghi et al., 2020; Mulargia et al., 2018; Sillero et al., 2018; Bellati et al., 2019; Senczuk et al., 2019; further references are given as supplementary material L1). At the same time, recent paleontological investigations (see Zoboli et al., 2019, 2022, and literature therein) are providing interesting baseline information testifying for the presence of taxa that are present in Sardinia since a relatively deep past (as green toads, *Emys orbicularis*, *Testudo hermanni*, *Natrix*) or went locally extirpated (as *Speleomantes*, *Discoglossus*, *Salamandrina, Mauremys*, giant tortoises, softshell turtles, worm lizards, agamid lizards, *Timon*, *Vipera*) or even globally extinct ('*Tomistoma*' *calaritanus*, *Trachyaspis lardyi*, *Testudo pecorinii*, pleurodiran turtles, *Sardophis elaphoides*).

With this work, we aim to provide updated distribution data collected from literature and direct field observations, together with a critical comment on the diversity of the Sardinian herpetofauna. Although distribution databases are a dynamic tool constantly updated, we still believe it is important to take "snapshots" of the distribution of the various species from time to time to promptly identify potential critical issue and intervene with appropriate conservation measures.

A particular focus was also made on the fauna of satellite islands, with an updated list of amphibians and reptiles of the circum-Sardinian islands that actively contribute to the herpetological diversity of Sardinia.

MATERIAL AND METHODS

Study site and data source, maps

Sardinia is located in the western Mediterranean and is one of the largest Italian regions. The island has an area that slightly exceeds 24,000 km^2 and is characterized by a diversified territory consisting of plains, plateaus, hills, and mountains, as well as an extensive and varied geomorphological coastline and numerous satellite islands, islets, and rocks.

The data on the distribution of amphibians and reptiles derive from both literature review and direct observations in the field carried out since 2005 until July 2022. Surveys have been carried out at different altitudes and visiting different types of natural and anthropogenic habitats, both by day and by night. Each data has been georeferenced with a satellite radio navigation device (Global Positioning System-GPS), or has been attributed to a toponym reported by the IGM maps (*Istituto Geografico Militare*). All data are stored in the database of the Sardinian Section of the Italian Society of Herpetology (SHI) "*tilighelta*". The dataset was enriched with bibliographic (e.g., Corti et al., 2000; Bassu et al., 2008, 2010, 2013; Salvi & Bombi, 2010; De Pous et al., 2012; Cossu et al., 2018; Mulargia et al., 2018) and with museum records (MZUF).

For the elaboration of species distribution maps, we used the UTM (Universal Transverse Mercator Projection, Coordinate Reference System WGS84 / UTM zone 32N) grid (10 × 10 km), dividing the island into 312 meshes. Bibliographic data without exact coordinates were reported in the respective UTM mesh. Each map shows data prior to 2010 and new data recorded from 2010 until July 2022. Other categories represented in the maps for some species are: a) doubtful records; b) single sporadic observation, referred to single individuals found out of the species range; c) multiple sporadic observations, when more than one individual was observed - simultaneously or over time – out of the species range (e.g., translocated *Testudo* spp.). The species distribution maps (see supplementary material) were produced using QGIS 3.14.16-Pi (QGIS.org, 2022).

Study species

The complete list of amphibian and reptile species inhabiting Sardinia is given in Table 1, where the endemic species are also indicated; Table S1 (supplementary material) reports the updated list of the herpetofauna of the circum-Sardinian islands. The species nomenclature follows Speybroeck et al. (2020). The presence of *Zamenis lineatus/longissimus* in Sardinia is currently debated (Razzetti and Zanghellini, 2006) and therefore here not reported. Introduced species with a relatively wide distribution are reported (e.g., *Trachemys*), while those recorded only through sporadic encounters of single individuals (e.g., *Mauremys*) are not. Due to ongoing studies on the presence of different *Pelophylax* species, all the observations related to the species of this genus are reported in a single map. However, in Table 1 they are all listed.

Table 1. List of amphibians and reptiles of Sardinia. The endemic species are marked as follow: EEE = exclusively endemic to Sardinia; EE = Endemic to Sardinia and Corsica; E = Endemic to the Central-Western-Mediterranean.

Amphibia	
Euproctus platycephalus (Gravenhorst, 1829)	EEE
Speleomantes flavus (Stefani, 1969)	EEE
Speleomantes genei (Temminck & Schlegel, 1838)	EEE
Speleomantes imperialis (Stefani, 1969)	EEE
Speleomantes sarrabusensis Lanza, Leo, Forti, Cimmaruta, Caputo & Nascetti, 2001	EEE
Speleomantes supramontis (Lanza, Nascetti & Bullini, 1986)	EEE
Bufo bufo (Linnaeus, 1758)	
Bufotes viridis balearicus (Boettger, 1880)	
Discoglossus sardus Tschudi, 1837	E
Hyla sarda (De Betta, 1857)	E
Pelophylax bedriagae (Camerano, 1882)	
Pelophylax bergeri (Günther, 1986)	
Pelophylax kurtmuelleri (Gayda, 1940)	
Reptilia	
Emys orbicularis (Linnaeus, 1758)	
Trachemys scripta (Thunberg in Schoepff, 1792)	
Testudo hermanni Gmelin, 1789	
Testudo graeca Linnaeus, 1758	
Testudo marginata Schoepff, 1792	
Euleptes europaea (Gené, 1839)	E
Hemidactylus turcicus (Linnaeus, 1758)	
Tarentola mauritanica (Linnaeus, 1758)	
Algyroides fitzingeri (Wiegmann, 1834)	EE
Archaeolacerta bedriagae (Camerano, 1885)	EE
Podarcis siculus (Rafinesque, 1810)	
Podarcis tiliguerta (Gmelin, 1789)	EE
Chalcides chalcides (Linnaeus, 1758)	
Chalcides ocellatus (Forskål, 1775)	
Hemorrhois hippocrepis (Linnaeus, 1758)	
Hierophis viridiflavus (Lacépède, 1789)	
Natrix helvetica cetti Gené, 1839	EE
Natrix maura (Linnaeus, 1758)	

Data analyses

Analyses were performed excluding sporadic observation (mainly related to *Testudo*), doubtful observations, and *Trachemys* spp. as an alien species that in recent times spread on the islands.

For each UTM mesh, we extrapolated the following environmental variables: number of Corine Land Cover classes, classified at level 3 (NCLC$_3$; Kosztra et al., 2019); index of environmental heterogeneity increasing with NCLC$_3$ and number of land use polygons (HETER = NCLC$_3$ × N polygons / mesh surface); index of edge density (ED = perimeter/surface calculated on land uses' polygons; we considered the mean value per mesh); maximum elevation (Elev); elevation range (ΔElev); abundance of wetlands (WET, the relative surface occupied, in a UTM mesh, by polygons belonging to the CLC classes Wetlands and Waterbodies). For each UTM mesh, we also extrapolated the number of all species (NTOT); endemic species (N_ETOT, *Discoglossus sardus, Euproctus platycephalus, Speleomantes* spp., *Hyla sarda* among amphibians; *Algyroides fitzingeri*, *Archaeolacerta bedriagae*, *Euleptes europaea*, *Natrix helvetica cetti*, *Podarcis tiliguerta* among reptiles); amphibian species (NAmph); endemic amphibian species (N_EAmph); reptile species (NRept); endemic reptile species (N_ERept). Even if the total number of species was correlated with those of amphibians and reptiles (considering all species and the endemic ones; tested with Pearson correlation, see Results), we performed analyses on all the six categories of species abundance, in order not to miss possible meaningful differences.

To test if the species abundance per UTM mesh varied depending on the above-listed environmental variables (NCLC$_3$, HETER, ED, Elev, ΔElev, WET), we used generalized linear models (GLZ) with, in turn, NTOT, N_ETOT, NAmph, N_EAmph, NRept, N_ERept, as dependent variable, with Poisson error distribution. We performed stepwise regression, and we selected the best-fit model according to the Akaike Information Criterion (we selected the models with the lowest AIC; Burnham and Anderson, 2002).

RESULTS

Sardinia falls inside 312 grid meshes, seven of which occupied by a very small terrestrial surface (<1 ha to about 37 ha). We analysed 7016 records: 1416 records of 11 species of amphibians and 5600 records of 18 species of reptiles. Most of the meshes were characterized by the presence of 1-3 amphibian species (73%; Figure 1) and 6-8 or 9-11 reptile species (32% with 6-8 species, 30% with 9-11 species; Figure 2). Distribution maps (on 10 × 10 km UTM grid) of the 29 species are provided as supplementary materials.

NTOT was correlated with NAmph ($N = 312$, $r = 0.697$, $P < 0.001$) and NRept ($r = 0.961$, $P < 0.001$); N_ETOT with N_EAmph ($r = 0.772$, $P < 0.001$) and N_ERept ($r = 0.870$, $P < 0.001$). Results of the analysis of the pattern of species abundance per UTM mesh (model selection and following GLZs) are shown in Table 2 and 3. NTOT decreased in those meshes with higher maximum elevation but, at the same time, was favoured by increas-

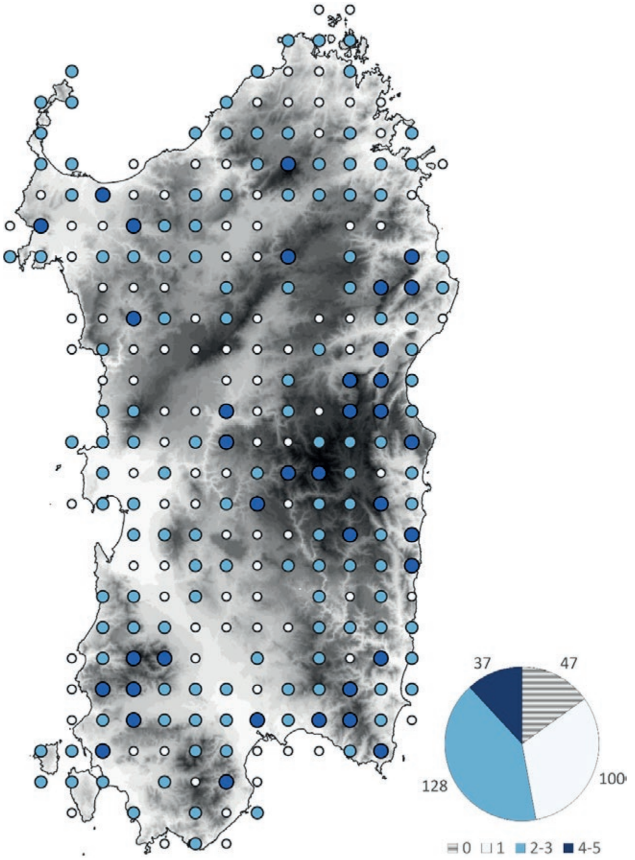

Fig. 1. Number of amphibian species in UTM 10 × 10 km grid meshes. Dots in the map indicate the presence of 1 (white small dot), 2-3 (small dot, in light blue), 4-5 (big dot, in dark blue) species. The pie chart summarizes the number of meshes hosting different ranges of species abundance, including those meshes with no species.

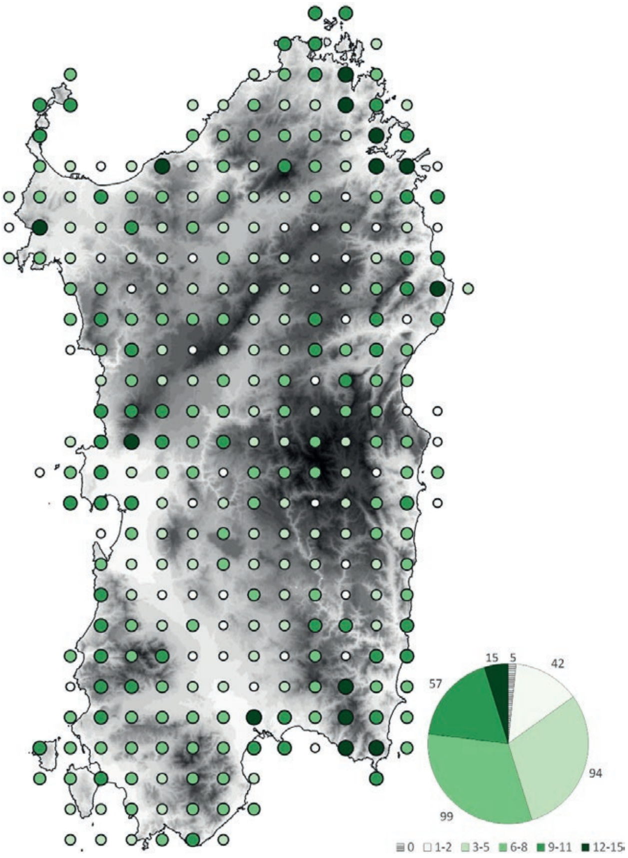

Fig. 2. Number of reptile species in meshes UTM 10 × 10 km grid. Dots in the map indicate the presence of 1-2 (small white dot), 3-5 (small light green dot), 6-8 (medium light green dot), 9-11 (medium dark green dot), 12-15 (dark green dot) species. The pie chart summarizes the number of meshes hosting different ranges of species abundance, including those meshes with no species.

Table 2. Akaike Information Criterion (AIC) in the selection of the best model explaining the pattern of abundance of all amphibian and reptile species (NTOT, NAmph, NRept) and of only endemic species (N_{ETOT}, N_EAmph, N_ERept) per UTM mesh, considering the following predictors: number of land cover classes ($NCLC_3$), index of environmental heterogeneity (HETER), index of edge density (ED), maximum elevation (Elev), elevation range (ΔElev), abundance of wetlands (WET); *w* = Akaike weight of the best model; w_1/w_2 = Akaike weight ratios between the first and second ranking models.

Response variable	Predictors	AIC	*w*	w_1/w_2
NTOT	HETER; Elev; ΔElev; $NCLC_3$; ED	1667.340	0.326	1.310
N_ETOT	HETER; ΔElev; ED	1158.529	0.139	1.014
NRept	HETER; Elev; ΔElev; $NCLC_3$; ED	1525.052	0.315	1.721
N_ERept	HETER; ΔElev; $NCLC_3$; ED	955.4630	0.283	2.594
NAmph	HETER; ΔElev; ED; WET	795.2846	0.188	1.141
N_EAmph	ΔElev; ED; WET	800.9570	0.259	1.830

ing elevation range, number of land uses and edge density. Not surprisingly, given the numerical preponderance of reptiles on the total amount of data, the predictors selected when considering all reptiles were the same selected for NTOT, with the small difference that, among those with a significant effect, there was the index of heterogeneity instead of $NCLC_3$. On the contrary, considering all amphibians, the selected predictors with a signif-

Table 3. GLZ testing the effects of the environmental variables selected by models in Table 2 on the abundance of all species (NTOT, NAmph, NRept) and of only endemic species (N_E, N_EAmph, N_ERept) per UTM mesh.

Response var.	Predictors	df	Estimates	Wald - Stat.	P
NTOT	Intercept	1	0.931	57.444	0.000
	HETER	1	0.006	2.896	0.089
	Elev	1	-0.001	18.820	0.000
	ΔElev	1	0.001	20.167	0.000
	NCLC$_3$	1	0.017	5.297	0.021
	ED	1	0.018	52.524	0.000
N_ETOT	Intercept	1	-0.222	1.263	0.261
	HETER	1	-0.000	0.000	0.999
	ΔElev	1	0.001	54.109	0.000
	ED	1	0.019	26.551	0.000
NRept	Intercept	1	0.840	39.018	0.000
	HETER	1	0.008	4.263	0.039
	Elev	1	-0.001	20.727	0.000
	ΔElev	1	0.001	14.647	0.000
	NCLC$_3$	1	0.015	3.089	0.079
	ED	1	0.017	38.575	0.000
N_ERept	Intercept	1	-0.321	1.852	0.174
	HETER	1	0.002	0.200	0.654
	ΔElev	1	0.001	24.799	0.000
	NCLC$_3$	1	-0.033	12.875	0.000
	ED	1	0.018	4.563	0.033
NAmph	Intercept	1	-0.739	4.879	0.027
	HETER	1	0.025	2.526	0.112
	ΔElev	1	0.001	17.858	0.000
	ED	1	0.0178	7.973	0.005
	WET	1	-0.2488	5.259	0.027
N_EAmph	Intercept	1	-1,238	16.129	0.000
	ΔElev	1	0.018	46.501	0.000
	ED	1	0.001	15.233	0.000
	WET	1	0.019	0.712	0.399

icant effect on the abundance of species per mesh were ΔElev, ED, and the relative abundance of wetlands.

Focusing on endemic species, the abundance of all species was significantly influenced by ΔElev and ED (HETER was selected, but it had no significant effects) (Table 2 and 3). NCLC$_3$ was added to these predictors when analysing endemic reptiles, and WET when analysing endemic amphibians, but without a significant effect (Table 2 and 3).

DISCUSSION

The maps we obtained in this work represent an important improvement on the distribution of amphibians and reptiles in Sardinia. Compared to previous publications (Sindaco et al., 2006; Bassu et al., 2008, 2010, 2013), the area surveyed for each species has been widely implemented (percentage increase of UTM meshes compared to Sindaco et al., 2006: e.g., *Euproctus platycephalus* 142%, *Speleomantes* spp. 0-115%, *Bufotes viridis balearicus* 632%, *Discoglossus sardus* 130%, *Hyla sarda* 379%; *Euleptes europaea* 228%, *Hemidactylus turcicus* 226%, *Emys orbicularis* 518%, *Testudo hermanni* 370%, *Algyroides fitzingeri* 121%, *Archaeolacerta bedriagae* 58%, *Podarcis tiliguerta* 142%, *Chalcides ocellatus* 105%, *Hierophis viridiflavus* 130%, *Natrix helvetica* 54%). By examining the distribution of the single species, it is to be noted that almost all the endemic species are missing in the plains of Nurra and Campidano (NW and SW Sardinia, respectively). Only in a few places, some of the endemic species occur in these regions. In particular, the distribution of the endemic lizards *Algyroides fitzingeri* and *Podarcis tiliguerta* very rarely includes wetlands and intensively cultivated plains where they have been observed only in "edge" contexts, while *Archaeolacerta bedriagae*, being a rupicolous species, is found exclusively in rocky habitats, from sea level to high altitudes (Sindaco et al., 2010). Approximately the same applies to *Euleptes europaea*, a tiny gecko also widely distributed in micro-insular systems. Only *Hyla sarda*, among endemic species, being particularly linked to lentic waters, has settled in these two aforementioned plains.

Among the amphibians and in particular among Urodela, the endemic and/or sub-endemic species, such as the endemic Sardinian brook newt, *Euproctus platycephalus*, and the cave salamanders, *Speleomantes flavus, S. genei, S. imperialis, S. sarrabusensis, S. supramontis* (the ranges of these last five species do not overlap), are distributed on the main island exclusively in hilly and mountain environments. It is interesting to note that four species of Testudines live in Sardinia, one Emydidae and three Testudinidae: the native freshwater European pond terrapin, *Emys orbicularis* and *Testudo hermanni*, whose presence on the island seems to date back to the Early Pleistocene (Biello et al., 2021; Zoboli et al., 2022) and, *T. graeca* and *T. marginata*. The populations of these last two species settle in distinct areas of the island despite *T. marginata*, whose large size often makes this species a preferred target of illegal collection and translocation, is the most easily observed in areas far from its primary Sardinian range. As for snakes, four species inhabit the island. The distribution of the endemic *Natrix helvetica cetti* (Schultze et al. 2020), a relatively elusive subspecies, follows the distribution pattern of the other endemic taxa, according to his rupicolous habits and avoidance for plains (Vanni & Cimmaruta, 2010; Lunghi et al., 2019). *Hierophis viridiflavus*, is certainly the most widespread snake found on the Island whereas *Hemorrhois hippocrepis*, whose presence in the past has been reported in much of south-western Sardinia (Bruno and Hotz, 1976), seems to have restricted its range to such an extent that, in the last decade, it has been reported only for the city of Cagliari and its surroundings. Contrary to what is known for this species, considered rather xerophilous (Zuffi, 2006), the Sardinian population of *H. hippocrepis* lives near wetlands, in agricultural habitats and in urban areas.

As for the green frogs, *Pelophylax* spp., further research is needed to draw a clear picture of the distribution of the different taxa on the island, given that *P. kurtmuelleri*, *P.* cf. *bedriagae* and *P. bergeri* populations have been detected (Bellati et al., 2018). The introduced *P. kurtmuelleri* and *P.* cf. *bedriagae* can be considered naturalized following Bellati et al. (2019). The latter species is found in both northern and southern Sardinia. The settlement of the introduced green frogs may be favoured by vacant niches, even though the particularly dry climate could limit their expansion (Bellati et al., 2017, 2018, 2019).

When analysing how the number of species varies in relation to several environmental variables, the importance of elevation range and edge density in determining the abundance of herpetofauna species emerges. Indeed, increasing the elevation range usually entails a higher habitat diversity, and edge habitats (including, for instance, ecotones and riparian boundaries) are well known key elements for the herpetofauna.

The comparison between the factors influencing the abundance of all species and of those influencing the abundance of endemic species only reveals further interesting insights. For instance, the total number of species decreases in mountainous areas (that is those included in meshes with higher maximum elevation), while this was not a limiting factor for endemic species, many of which are also found at high altitudes.

When focusing on all amphibians, the relative abundance of wetlands was among the factors influencing species abundance, whereas it was not selected as significant factor when analyzing the endemic species, *Hyla sarda*, *Discoglossus sardus*, and *Speleomantes* spp. Indeed, these amphibians often spawn in minor water bodies, not included in the CLC classification as “Wetlands” and “Waterbodies”, or in underground environments as in the case of *Speleomantes*.

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SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found at <http://www-9.unipv.it/webshi/appendix/index.html> manuscript number 13627

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