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ORIGINAL ARTICLE

Contribution of the public to the modelling of the distributions of species: Occurrence and current and potential distribution of the ant *Manica rubida* (Hymenoptera: Formicidae)

Patrick KRAPF

Molecular Ecology Group, Department of Ecology, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria;
e-mail: patrick.krapf@uibk.ac.at

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Abstract. Maps and models of the distributions of animals and plants are important for assessing their current and future status. Such models rely on information on the environment and occurrence of species. While data on the environment are often easily gathered that on the occurrence of species is often tedious and expensive to collect. An easy way to gather data on species occurrences is to use online platforms such as GBIF or iNaturalist, which rely on the public. This data can be used to produce maps and develop models of the distributions of various animals, such as ants. Even though there are a few in depth studies on the distributions of ant species, knowledge of the distribution and status of many species is lacking. One such species is the widespread ant *Manica rubida*, which is currently not included in the international Red List. Here, data on the occurrence of *M. rubida* recorded in online platforms, literature and collected during a field survey were used to develop a map of its distribution and a species model, in order to evaluate its current status. A total of 611 occurrences were found and indicate that this species mainly occurs in the European Alps and other Eurasian mountain ranges. Records of most occurrences were obtained from online platforms and the number increased significantly over the last two decades and indicate this species occurs over an altitudinal range of 3000 m. The species model revealed that there are potential areas of suitable habitat for *M. rubida* in the Pyrenees, European Uplands, Pindus Mountains, Balkan Mountains and Pontic mountains. Currently, *M. rubida* does not seem to be threatened by climate change, but it is recommended that the monitoring of its distribution should be continued. This study reveals that data from online platforms can provide the information necessary for developing species models, which can be used to assess the current status and estimate the potential effect of climate change on a species and plan conservation strategies.

INTRODUCTION

Maps of the distributions of species and species distribution models (SDMs) are important for assessing the distribution and status of plants and animals. Such models estimate the habitat preference, suitability and distribution of a species based on their presence or absence in areas and data on the environment (e.g., average temperature and precipitation) (Franklin, 2009). In SDMs, these input variables are correlated in order to assess the relationship between local environmental data and occurrences. Over the last few decades, SDMs have been widely used for ecological and biogeographical inference (Elith & Leathwick, 2009; Guillera-Arroita et al., 2015), plan conservation strategies (Foden et al., 2019) and predict potential areas for colonisation by other, potentially invasive, species (Guillera-Arroita et al., 2015). SDMs are also frequently used to predict potential future distributions of species and assess the threat of extinction due to climate change (Araújo et al., 2006). The number of future-projection SDMs increases constantly, which greatly facilitates the development of strategies and plans for conservation (Ferraz et al., 2021).

To produce reliable SDMs, detailed environmental data and valid occurrences are needed. Environmental data can often be obtained rather quickly (e.g. by downloading variables from WorldClim; Fick & Hijmans, 2017). In contrast, gathering species occurrences is often tedious, time-consuming and expensive, and requires a high level of taxonomic knowledge to identify the species (Wäldchen et al., 2018; Geisen et al., 2019). Although the number of SDMs has increased over the last few decades (Zimmermann et al., 2010), they are not available for many species mainly due to a lack of information on where they occur. Moreover, an SDM that is based on only a few occurrences often poorly represents the real distribution of a species (Choe et al., 2016; Biber et al., 2020). Gathering valid occurrence data is thus important for SDMs. It involves careful planning and surveying spatially large areas of potential distribution in order to detect whether a species is present or absent. Thus, lack of time and/or funding often results in the recording of few occurrences, which impedes the generation of SDMs and planning of conservation strategies for many species.

Online projects and platforms are possible quick and easy available sources of data on the occurrence of a species. Such projects and platforms enable researchers to use data recently collected by researchers and the public to create SDMs or use such data in other research projects. Various online projects and platforms exist, with some of them taxon-specific, while others include data on numerous plant and animal species. For example, taxon-specific projects exist for birds [e.g., eBird (https://ebird.org/home), Xeno-canto (https://xeno-canto.org/), Brazilian WikiAves (https://www.wikiaves.com.br/)] and social insects [e.g., Bees, Wasps & Ants Recording Society, BWARS (https://www.bwars.com/)]. Other projects such as the Global Biological Information Facility (GBIF, https://www.gbif.org/), iNaturalist (https://www.inaturalist.org), or specific Facebook groups (Marcenò et al., 2021) include data on many species. Such projects and platforms are easily accessible to the public and are great way of involving amateur naturalists in research (McKinley et al., 2017). In the case of iNaturalist, amateur naturalists upload pictures of their observations to the platforms (including the date and GPS coordinates). Then, identifiers validate the pictures, and the observations become "research grade" as soon as 2/3 of identifiers agree on a species-level ID. This procedure ensures that valid identifications are readily available. The inclusion of amateur naturalists on such platforms greatly enhances the detection of species occurrences and enables researchers to produce maps and models of the distributions of species (McKinley et al., 2017). Moreover, the number of users of such online platforms has drastically increased over the last decades (Di Cecco et al., 2021; Unger et al., 2021). Amateur naturalists are thus adding crucial data to such platforms and projects that can be used by the scientific community to create and/or update SDMs (Crall et al., 2015; van der Wal et al., 2015; Maund et al., 2020; Zulian et al., 2021). Consequently, this greatly increases our knowledge of the distributions of various (potentially-invasive) species, such as ants.

Ants are an ecologically important and abundant group in terrestrial ecosystems (Alonso, 2009) and are present on all continents, except Antarctica (Parr & Bishop, 2022). They provide important ecosystem services such as dispersing seeds, pest control and soil bioturbation (Parr & Bishop, 2022). However, ants are also among the worst invasive species and cause economic damage globally (Bertelsmeier, 2021). With some exceptions, many ant colonies are quasi-sessile, that is, they do not relocate to new areas (Menzel & Feldmeyer, 2021). Ants, thus, have to adjust to the environment and changes in climate. Ants can also be easily sampled and re-sampled (Agosti et al., 2000), so it is possible to determine whether they persist over time. In addition, local environmental conditions can be recorded continuously using data loggers or whenever ant colonies are visited. These features make ants suitable species for modelling their distribution and creating conservation plans, for example, for detecting a decrease or increase in the number of threatened or invasive species, respectively, or for evaluating the effectiveness of conservation plans and assessing long-term changes in the ecosystem (Underwood & Fisher, 2006). Ants are also a group of animals that have attracted public interest over the last few years, especially during spring (Queiroz et al., 2021). Importantly, experts can quickly teach amateur naturalists how to identify ants to the genus level (e.g., wood ants). Some ants can also easily be determined visually to species level, based on their shape, colour and habitus, such as, for example, some species of the genera *Acromyrmex*, *Atta* (Fowler et al., 1989), *Camponotus, Crematogaster, Dolichoderus* and *Pheidole* (Souza et al., 2016). Other easily recognisable species are *Cryptopone ochracea* (Báthori et al., 2022) and *Manica rubida*.

Manica rubida is the largest myrmicine in Europe. It is easily recognized based on its size, colour, and lack of spines on its propodeum (Seifert, 2018). The workers range from 5 to 8 mm in length, with a reddish yellow or brownish red colour and the males are completely black (Wheeler & Wheeler, 1970). In Europe, *M. rubida* occurs between 250 and 2500 m above sea level (m a.s.l.), mainly in Alpine regions (Wheeler & Wheeler, 1970; Seifert, 2018). It lives in soil nests in swamps and moist meadows, riparian and sandy open habitats (Wheeler & Wheeler, 1970; Seifert, 2018). It is moderately thermophilous and slightly hygrophilous (Wheeler & Wheeler, 1970; Seifert, 2018). It occurs in a geographically large area (latitudinal range 37°N to 52°N) (Seifert, 2018) and is likely to be affected by climate change, especially at low latitudes and altitudes as climate changes more drastically at high altitudes (Lamprecht et al., 2018; Rogora et al., 2018; IPCC, 2021, 2022). Its status based on the IUCN Red List (https://www.iucnredlist.org/) is "not evaluated" (https://eunis.eea.europa.eu/species/87882#threat_status), whereas some local red species lists report it as not threatened or near threatened (Rabitsch et al., 1999; Schlick-Steiner et al., 2003; Seifert, 2011). Although there is some data on the occurrence of *M. rubida*, there exists currently no map of its distribution. This study aims to increase the level of knowledge of the distribution of *M. rubida* by creating a map of the occurrence of this species and an SDM using records of its occurrence from online projects and platforms, the literature and a field survey. Both the map and the SDM will enable assessments of the current and potential distribution of *M. rubida*, assessing whether data from online projects and platforms facilitate the creation of SDMs and evaluating the extent *M. rubida* is threatened by climate change.

MATERIALS AND METHODS

Collecting records of occurrence

Data on the occurrence of *M. rubida* were obtained from three sources: (1) Downloaded from several online platforms, namely GBIF (retrieved on 22.01.2023; GBIF Occurrence Download https://doi.org/10.15468/dl.vgvkxf), iNaturalist (retrieved on 22.01.2023), AntWeb (https://www.antweb.org) and AntMap (Janicki et al., 2016; Guénard et al., 2017) (both on 24.06.2022).

(2) In addition, Web of Science and Google Scholar were used to search for literature on *M. rubida* and local checklists (English or original languages) and included the following keywords: "Manica rubida" "ant" "checklist" "country", (where "country" is a placeholder for multiple countries, namely Albania, Bulgaria, Croatia, Czech Republic, Georgia, Greece, Montenegro, Poland, Romania, Russia, Slovakia, Slovenia, Turkey, Ukraine). The retrieved literature was searched for records of occurrences that included GPS coordinates. For all GPS coordinates that lacked information on altitude, the online tool "Find altitude by coordinates" (https://www.advancedconverter.com/map-tools/find-altitude-by-coordinates) was used to calculate the altitude. (3) In addition, to the online search, a survey to find *M. rubida* colonies in the field was undertaken in Tyrol, Austria, specifically in riparian habitats and at high altitudes, in order to increase the number of occurrences. For all occurrences, a document was curated manually, which included the GPS coordinates, altitude, locations sampled and date, country and quality of the data (e.g., research quality; see supplementary material).

Statistical analyses of sources, year sampled, countries and altitude

For all statistical analyses, only occurrences from GBIF and iNaturalist that were graded as of research-quality and had GPS coordinates were used. For occurrences from AntMap, AntWeb, BinsBoldSystem, and Literature, research-quality was assumed. The occurrences were categorised, namely by source (i.e., AntMap, AntWeb, BinsBoldSystem, GBIF, GBIF SwissOccurence-Points, iNaturalist, Literature), year of sampling ("–1" was used for entries without a year), countries and altitude. The altitudinal range was arranged in five bins each spanning 500 m (0–500, 500–1000, 1000–1500, 1500–2000, 2000–2500 and higher). Countries with a mean altitude higher than 300 m a.s.l (retrieved from https://www.cia.gov/the-world-factbook/field/elevation/) were defined as partially mountainous. For each of these categories (source, year of sampling, etc.), a generalized linear model (GLM) fitting a Poisson model for count data was calculated in RStudio v 2022.12.0 (RStudio Team, 2022) and using R version 4.2.1 (R Core Team, 2022) to assess whether the number of occurrences differed between the groups within each category, except for the year sampled. For the year sampled, a linear regression was calculated to test whether the number of samples increased over the years. Model fit was checked visually using the DHARMa package (Hartig, 2022). Here, the number of samples was log-transformed because the model fit indicated that the residuals were not normally distributed. In more detail for the category's source, country and altitude: For source, it was tested whether the number of occurrences differed between the groups. For country, it was tested whether the number of occurrences differed between countries. For altitude, it was tested whether the number of occurrences differed between the above-mentioned five ranges of altitude.

Map of distribution and SDM

For the map of the distribution and SDM, duplicates of occurrences and those recorded in North America and Africa were removed. The latter occurrences are dubious as they are not within the known range of *M. rubida* (AntMaps; Guénard et al., 2017). The map of the distribution and SDMs were created in R using several packages for data extracting, cropping, plotting, etc. using the packages caret (Kuhn, 2022), dplyr (Wickham et al., 2022), ENMeval (Muscarella et al., 2014), maptools (Bivand & Lewin-Koh, 2022), PerformanceAnalytics (Peterson & Carl, 2022), raster (Hijmans, 2020), rgdal (Bivand et al., 2022) and sp (Bivand ey al., 2013). For details of the SDM, see the supplementary R script. For the map of the distribution, occurrences were plotted using ggplot2 (Wickham, 2016) onto a map of Europe using the above-mentioned five ranges of altitude.

To create SDMs, all 19 Bioclim variables and altitude were downloaded as shape files from the WorldClim version 2.1 dataset (Fick & Hijmans, 2017) at a resolution of 2.5 min, which approximates an area of 4 to 4.5 km^2 at the equator. As *M. rubida* is predominantly present in mountainous areas and slope may be important for its presence, slope was calculated using the elevation shape file and the terrain function (raster package). SDM was developed using the "ENMevaluate" function and the "maxnet" algorithm (ENMeval package). The "maxnet" algorithm uses the same model structure as the standalone "MaxEnt" Java package (Phillips & Dudik, 2008; Philipps, 2021). MaxEnt contrasts presence against background points (Phillips & Dudik, 2008). By default, MaxEnt uses 10,000 background points. For *M. rubida* SDMs, 40,000 randomly selected background points were used because the area of study extends over a large and heterogeneous part of Eurasia and ensured that all possible environments in Eurasia are represented (Elith et al., 2011). Moreover, occurrences and background points were divided into partitions by applying a random-K fold partition.

To select the best model, 20 separate SDMs were developed using a set of parameter combinations (regularisation multiplier and feature classes). In more detail, a combination of the regularisation multiplier (1 to 5) and feature classes (linear, quadratic, hinge and linear-quadratic-hinge) was used. The regularisation multiplier smooths the model, that is, a higher value results in simpler predictions and avoids fitting a model that is too complicated (Elith et al., 2011). The feature classes are used to create response curves (Merow et al., 2013). A model that only uses linear features is simpler than those using several features. The performance of each model was assessed using the area under the receiver operator curve (AUC), the 10-percentile omission rate, the Akaike information criterion corrected for small sample size (AICc) and deltaAICc value, which were all calculated using the ENMeval package. For the best model based on deltaAICc value, AUC value and 10-percentile omission rate, a null model was created. Null models are used to test if the model fits the occurrence data significantly better than a model built with randomly drawn occurrences (Raes & ter Steege, 2007; Kass et al., 2020). Both the complete R-script for the analyses and the occurrence data file are available as supplementary material.

RESULTS

Collecting records of occurrence and statistical analyses of source, year sampled, country and altitude

In total, 966 *M. rubida* occurrences were recorded in Eurasia. After duplicate removal, 611 occurrences remained and were used in subsequent analyses (a table with all occurrences is present in the supplementary material). For the descriptive analyses, the occurrences were categorised in terms of source, year sampled, country and altitude. For sources, the online platform iNaturalist included most of the occurrences with 222, followed by GBIF and GBIF Switzerland with a total of 139. In total, 433 occurrences were obtained from all online platforms (including AntMaps, etc.). During the field survey, further 38 occurrences were recorded. Overall, the online platforms AntMaps, GBIF, GBIF Switzerland, iNaturalist and the literature search (n = 78, literature search) yielded significantly

Table 1. Sources and number of occurrences, and the statistical analyses for each source.

Source	Number of occurrences	GLM z value	GLM p-value
AntMap	29	18.13	<0.001
AntWeb	24	–0.67	0.493
BinsBoldSystem	9	–3.06	0.002
GBIF	139	7.68	<0.001
GBIF SwissOccurencePoints	72	4.14	<0.001
iNaturalist	222	10.31	<0.001
Literature	78	4.55	<0.001
Sampling	38	1.10	0.273

Occurrences were obtained from different sources and classified based on the source. GLM z-values and p-values originate from a Poisson GLM, undertaken to determine whether the number of occurrences recorded in the various sources differed significantly assuming no difference between sources. Coloured cells indicate statistically significant differences between sources with a lower (BinsBoldSystem) or higher (AntMap, GBIF, iNaturalist, Literature) number recorded compared with other sources.

Table 2. The number of occurrences of *M. rubida* recorded in different periods of time.

Period	No. of occurrences added during this period	Total no. of occurrences
1932–2000		36
2001–2007 (2001 = launch GBIF)	60	96
2008–2014 (2008 = launch iNaturalist)	101	197
2015–today (22.01.2023)	337	534
No sampling date but locations given		77
Total		611

more occurrences than other sources such as AntWeb or the field survey (Poisson GLM expected under the assumption of no difference between sources, Null deviance: 431.74, df = 7, AIC: 62.096; Table 1).

Analysing the years sampled revealed that occurrences greatly increased over time, especially in the last two decades (LM, $R^2 = 0.21$, F = 32.3 on 1 and 119 DF, p-value: <0.001; Fig. 1, Tables 2, S1). The earliest occurrence is reported in a paper published in 1932 with 1 occurrence and the latest was retrieved in 2022 from iNaturalist. Most occurrences (n = 103) were recorded in 2022. Interestingly, most occurrences were recorded from 2018 to 2022 (Table S1). In the years after the launch of GBIF (2001) and iNaturalist (2008) until the end of 2014 (range of years 2001–2014), a total of 161 occurrences was recorded.

Manica rubida occurrences were recorded in 19 countries (Table 3), mostly in France (n = 145) followed by Switzerland (n = 124) and Austria (n = 105). Overall, significantly more occurrences of *M. rubida* were recorded in partially mountainous countries in Central Europe, such as Austria, Czech Republic, France, Italy and Switzerland, than in mainly flat countries such as Croatia, Germany and Poland, and flat and mountainous countries in Eastern and Southern Europe (e.g., Albania and Greece) (Poisson GLM expected assuming no difference between countries, Null deviance: 1036.30, df = 18, AIC: 115.79; Table 3). Partially mountainous countries include those with mean altitudes higher than 300 m a.s.l. Moreover, the occurrences increased significantly over time, especially over the last few decades and in mountainous areas such as Austria, France, Italy and Switzerland (Fig. 2).

Most occurrences were recorded between 1000 and 1500 m above sea level (n = 161; Table 4). Overall, significantly fewer occurrences were recorded at the highest altitudes than at all of the other ranges of altitude (Poisson GLM expected assuming of no difference between the five ranges of altitude, Null deviance: 43.84, df = 4, AIC: 43.03; Table 4). The altitudinal distribution of *M. rubida* is approximately 3000 m ranging from 6 m (Elmshorn, Schleswig-Holstein, Germany; GPS: 53.74877, 9.641509)

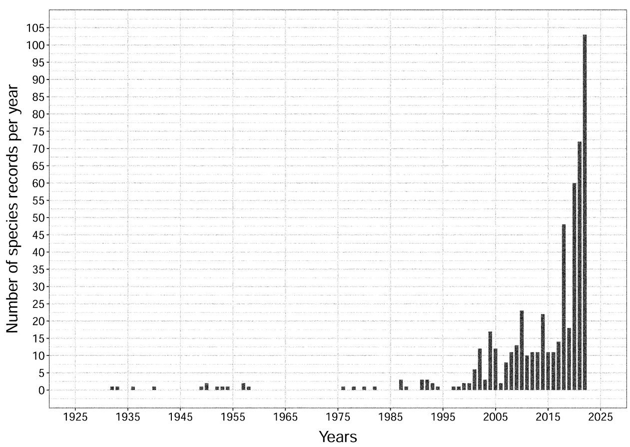

Fig. 1. The number of occurrences plotted against the year sampled. From 2000 onwards, the number of *M. rubida* occurrences steadily increased and peaked in 2022 with 103. The occurrences were obtained from online platforms, literature and a field survey. Please note that additional occurrences may be available as the search for occurrences was thorough, but not exhaustive.

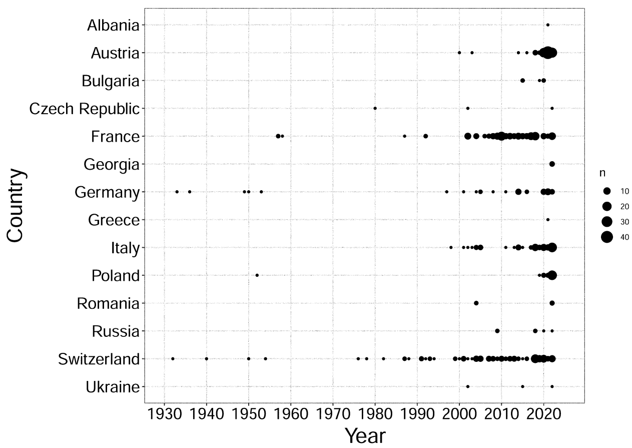

Fig. 2. The number of *Manica rubida* occurrences recorded for each country and year. The number increases over time for almost all countries. Please note that for some countries (Belgium, Bulgaria, Croatia, Montenegro, Slovenia and Turkey), no date was available. These countries are thus not depicted in Fig. 2 but are present in Fig. 3.

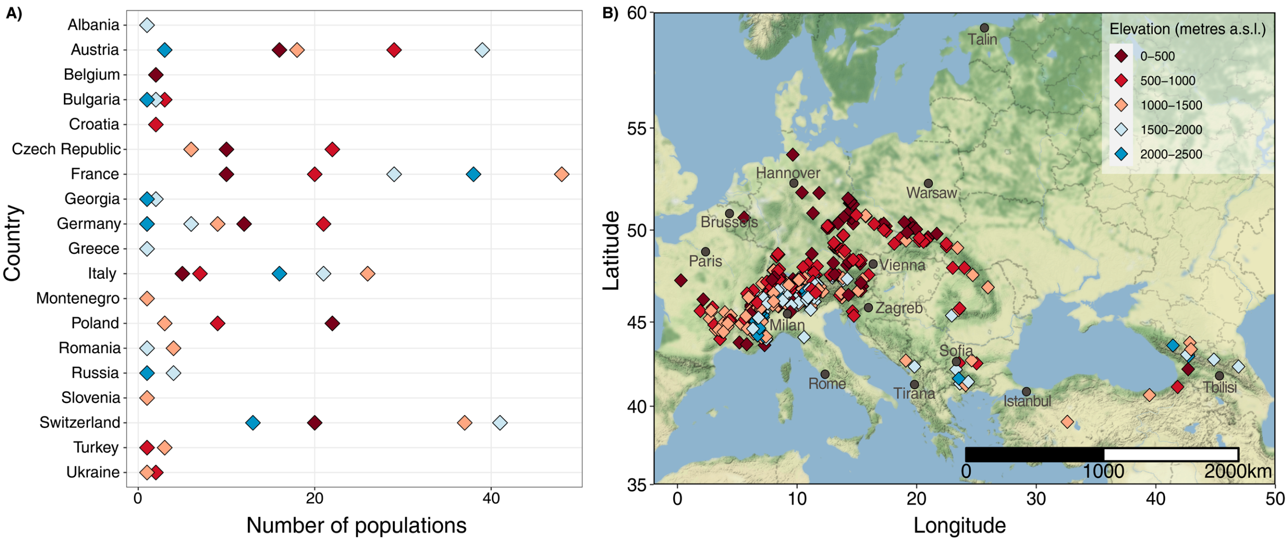

Fig. 3. A) The number of occurrences of *Manica rubida* recorded at each of five altitudinal ranges in each country. In some countries, occurrences are recorded at some but not all altitudes. B) A map of the distribution for *M. rubida* based 611 occurrences, which shows its distribution in Eurasia.

to 3098 m a.s.l. (Pelvoux, Vallouise-Pelvoux, France; GPS: 44.87347, 6.35645) (Fig. 3A). The map of its distribution revealed that *M. rubida* is predominantly present in mountainous regions, especially in the European Alps (Fig. 3B).

Modelling the distribution of *M. rubida*

A total of 20 models based on 463 occurrences were developed for *M. rubida*. This number of occurrences (n = 463) is slightly lower than the total number of occurrences recorded (n = 611) because ENMevaluate excludes multiple occurrences in the same grid cell and those that do not include all the environmental data (148 occurrences were excluded). The best SDM based on AUC, AICc and deltaAICc was the model using a regularisation multiplier of 1 and the feature classes linear, quadratic and hinge (Fig. 4, Table S2). The AUC, 10-percentile omission rate and AICc values of the best model were 0.96, 0.12 and 9835.98, respectively. The AUC, 10-percentile omission rate, and AICc values for all models ranged from 0.94 to 0.96, 0.1 to 0.12, and 9835.98 to 10369.47, respectively (Table S2). For all models, the deltaAICc (representing the difference between models) was always higher than when two are compared with the best-fitting model (Table S2). The location with the highest probability of finding *M. rubida* is the European Alps, especially in Austria, France, southern Germany, Italy (Northern Italy and Apennines), Lichten-

Table 3. The geographical details, number of occurrences recorded and results of statistical analyses of the data for each country.

Country	Mean altitude (m a.s.l.)	Dominant mountain range	Number of occurrences	GLM z value	GLM p-value
Albania	708	Dinaric Alps, Pindus	1	0.00	1.000
Austria	910	European Alps	105	4.63	<0.001
Belgium	181	—	2	0.57	0.571
Bulgaria	472	Balkans	7	1.82	0.069
Croatia	331	Dinaric Alps	2	0.57	0.571
Czech Republic	433	Carpathians	38	3.59	<0.001
France	375	European Alps, Central Massif	145	4.96	<0.001
Georgia	1432	Caucasus	5	1.47	0.142
Germany	263	European Alps, Mittelgebirge	49	3.85	<0.001
Greece	498	Pindus	3	0.95	0.341
Italy	538	European Alps, Apennine	75	4.29	<0.001
Montenegro	1086	Dinaric Alps	1	0.00	1.000
Poland	173	Carpathians	34	3.48	<0.001
Romania	414	Carpathians	6	1.66	0.097
Russia	600	—	6	1.66	0.097
Slovenia	492	Dinaric Alps	1	0.00	1.000
Switzerland	1350	European Alps	124	4.80	<0.001
Turkey	1132	Pontic Mountians	4	1.24	0.215
Ukraine	175	Carpathians	3	0.95	0.341

Occurrences were obtained for different countries and classified accordingly. The mean altitude was obtained from the World Factbook of the CIA (https://www.cia.gov/the-world-factbook/field/elevation/). GLM z-values and p-values stem from a Poisson GLM, which was carried out to assess whether the number of occurrences in the different countries differed assuming of no difference between the countries. Coloured cells indicate a statistically significant higher number of occurrences than in other countries.

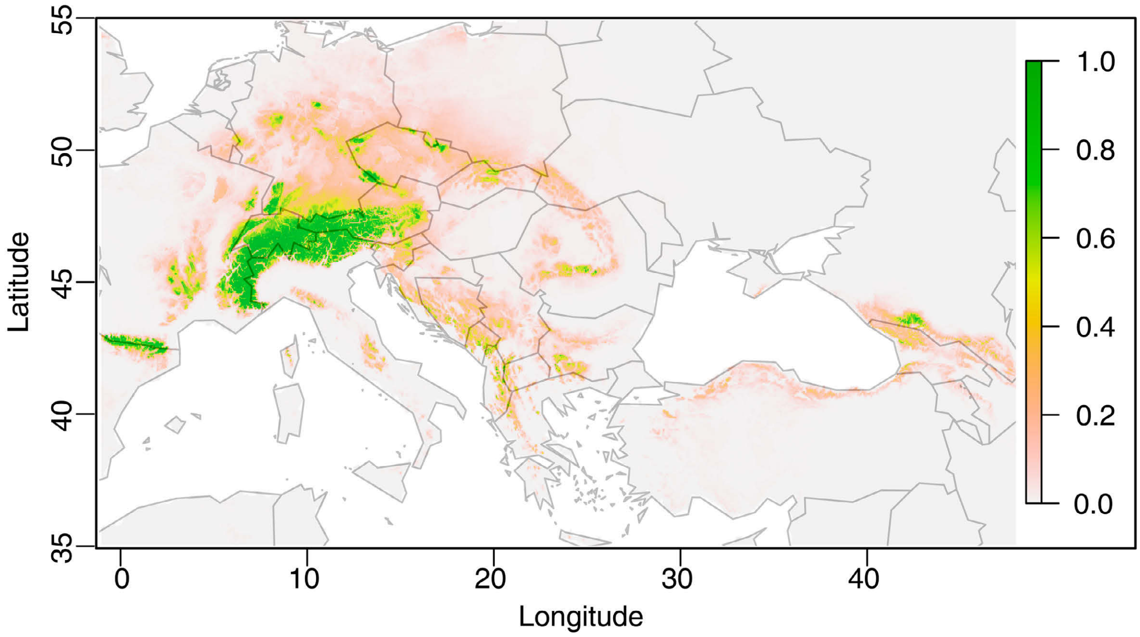

Fig. 4. A species distribution model (SDM) for Eurasia based on 463 *M. rubida* occurrences. The model indicates that for this species there is potentially a large area of suitable habitat in Eurasia, mainly in mountainous regions, such as, the European Alps, Pyrenees, Apennines, European Uplands, Dinaric Alps, Carpathians, Pindus Mountains, Balkan Mountains, Pontic mountains and Caucasus. The coloured legend indicates these potential areas of suitable habitat for *M. rubida* throughout the depicted geographic area. Green colour (1 in the legend) indicates a highly suitable area for *M. rubida*, whereas red and white colour (0 in the legend) indicate unsuitable areas.

stein and Switzerland (Fig. 4). The best-fitting SDM also predicts that there are potentially suitable areas for *M. rubida* in the Pyrenees, European Uplands, Dinaric Alps, Carpathians, Pindus Mountains, Balkan Mountains, Pontic Mountains and Caucasus (Fig. 4). A null model was created based on the SDM to assess whether it fits the occurrence data significantly better than a model built using randomly drawn occurrences. The AUC of the null model was 0.59 and the 10-percentile omission rate was 0.20 (Table S3). The SDM developed in this study fitted the occurrence data significantly better than the null model (AUC, z-score 12.50, p-value < 0.001; 10-percentile omission rate, z-score –1.99, p-value = 0.023).

DISCUSSION

In this study, 611 occurrences of *M. rubida* in Europe were collected from online platforms (e.g., GBIF, iNaturalist), literature and records collected in a field survey. The most occurrences for *M. rubida* were obtained from the online platform iNaturalist (n = 103), followed by GBIF (and GBIF Switzerland). Interestingly, many occurrences were only recently added to citizen-science platforms, specifically, over the last two decades. Of all the 19 countries where *M. rubida* is present, the most occurrences were recorded in France (n = 145), with highest number recorded between 1000 and 1500 m a.s.l. (n = 161). Using these occurrences, a first plot of the distribution of *M. rubida* was produced, which revealed that this ant is currently present in Central and Eastern Europe as well as Western Asia (latitudinal range from 36.5°N to 53.8°N, longitudinal range from 0.3°E to 46.9°E). Moreover, an SDM was developed that revealed that there are potential habitats for this ant in mountainous regions in Central Europe, specifically in the European Alps, but also in other regions in South-Eastern Europe and Eurasia (Fig. 4).

Highest and lowest altitudes and countries in which *M. rubida* was recorded

The highest numbers of occurrences were recorded between 1000 and 1500 m a.s.l. and also between 500 to 1000 and 1500 to 2000 m a.s.l. Seifert (2018) describes a similar altitudinal distribution. Interestingly, *M. rubida* occurs over an altitudinal range of more than 3000 m, from 6 m

Table 4. The number of occurrences recorded for each the five altitudinal ranges and results of the statistical analyses.

Altitudinal ranges (m a.s.l.)	Number of occurrences	GLM z value	GLM p-value
0–500	98	45.39	<0.001
500–1000	131	2.17	0.029
1000–1500	161	3.88	<0.001
1500–2000	147	3.11	<0.001
2000–2500 and higher	74	–1.82	0.068

Occurrences were obtained for five different altitudinal ranges. GLM z-values and p-values originate from a Poisson GLM used to assess whether the number of occurrences recorded differed assuming no difference between ranges. Coloured cells indicate statistically significant higher number of occurrences between ranges; m a.s.l. – metres above sea level.

a.s.l. in Germany to 3098 m a.s.l. in France. This finding extends the current altitudinal distribution of 500 to 2000 m a.s.l. (Seifert, 2018). Among the 19 countries where *M. rubida* occurs, most occurrences were recorded in France. This may be due to the two large mountainous areas present in France, namely the European Alps and the Massif central. Moreover, this high number of occurrences may also be due to the large population in France (total ca. 65.7 million people, 01.02.2023 https://statisticstimes.com/demographics/country/france-population.php), many of which live in mountainous areas. In contrast, the number of people living in mountainous countries such as Austria and Switzerland is much lower (ca. 9.1 and 8.8 million people, respectively; 01.02.2023 https://statisticstimes.com/demographics/country/austria-population.php and https://statisticstimes.com/demographics/country/switzerland-population.php), but higher in Germany (ca. 83.9 million people, 01.02.2023 https://statisticstimes.com/demographics/country/germany-population.php). Moreover, the geographic sizes of these countries differ greatly (Austria: 83,871 km^2; France: 643,801 km^2; Germany: 357,022 km^2; Switzerland: 41,244 km^2; 01.02.2023, https://statisticstimes.com/geography/european-countries-by-area.php), which is likely to have contributed to these differences. Even though Germany has a larger population than France, high altitude regions are only present in a small area in Germany. Thus it is likely that the more people living in mountainous areas in France accounts for the higher occurrence data recorded in online platforms there than in Austria, Switzerland and Germany.

The current distribution of *M. rubida* and its potential risk of extinction

The map of the distribution of *M. rubida* presented is the first for this species (Fig. 3B) and reveals that it is predominantly present in mountainous regions, mainly in the European Alps (Austria, France, Italy and Switzerland; Fig. 3B, Table 3) and the Carpathians (e.g., Czech Republic and Poland). In other countries, few occurrences are recorded (e.g., Bulgaria). These findings corroborate earlier studies that report its occurrence in mountainous regions (Wheeler & Wheeler, 1970; Seifert, 2018). The SDM indicates that its main area of distribution extends across the European Alps, with potentially suitable areas in the Pyrenees, Apennines, European Uplands, Dinaric Alps, Carpathians, Pindus Mountains, Balkan Mountains, Pontic mountains and the Caucasus, which is also corroborated by occurrences reported in some of these areas (Figs 3B–4).

The distribution model indicates that *M. rubida* is unlikely to be shortly directly threatened by loss of suitable habitat, which corroborates the current status of "not threatened" in Austria (Rabitsch et al., 1999; Schlick-Steiner et al., 2003; Wagner, 2014) and "near-threatened" in Germany (Seifert, 2011). Notably, the international IUCN Red List and lists of several countries (e.g., France, Italy, Switzerland) do not list this species. The status "not threatened" or "near-threatened" can arise due to (i) a species is either "not evaluated" or (ii) "data deficiency", that is, a lack of data. This indicates that a more detailed analysis of its status is needed in order to assess future risks and threats in these and other countries.

Even though *M. rubida* is not yet categorised as threatened in several Red Lists, it may soon, if not already, be affected by climate change, as it is a moderately thermophilic and slightly hygrophilic and nests below ground in swamps, meadows and riparian habitats (Seifert, 2018). With ongoing climate change, temperature will increase and more extreme events, such as droughts (e.g. in Europe in the summer of 2022; Toreti et al., 2022) are more likely to occur (IPCC, 2013, 2021). Droughts may negatively affect the area of suitable habitat for this species, especially in the European Alps. At high altitudes, temperature has already increased more than at low altitudes (Grabherr et al., 2010; Hämmerle et al., 2018; Ossó et al., 2022), especially over the last three decades (Marty & Meister, 2012), possibly resulting in a greater loss of suitable habitat at high altitudes. In contrast, high temperatures may also benefit this (and other) below-ground living species, which transports its brood along temperature clines in the soil in order to increase their rate of development, which, in turn, increases the colonies' rate of growth (Parr & Bishop, 2022). When the temperature exceeds *M. rubida*'s upper temperature threshold for development, however, this species may be adversely affected by climate change.

In addition, the dominant formicine ant *Formica fuscocinerea* may also decrease the area of suitable habitat currently available for the target species *M. rubida* at low altitudes as *F. fuscocinerea* is one of a few species that can dislodge the target species (Wagner, 2014) and is currently spreading into new areas. Strong interspecific dominance, abundance of workers and a lack of boundaries within supercolonies are considered to be the main traits resulting in the continuous spread of *F. fuscocinerea* in the European Alpine foreland (Witte, 2014; Pohl et al., 2018). With an increase in temperature, ants may become more aggressive (Krapf et al., 2023), possibly resulting in an increase in dislodging events. These two factors, drought and the advent of *F. fuscocinerea*, could, for example, result in an uphill movement of *M. rubida* and a narrowing of its area of suitable habitat as is reported for many other animal and plant species (Vitasse et al., 2021). Given the current potential area available and the data in Red Lists, the threat of extinction for *M. rubida* seems to be low compared with other species (Román-Palacios & Wiens, 2020). It is important, however, to continuously monitor *M. rubida* in order to assess if and how it adjusts to the effects of increasing temperature and the spread of *F. fuscocinerea*.

Contribution of the public to the modelling of the distributions of species

Of the different sources of occurrences, most occurrences were obtained from online platforms such as GBIF and iNaturalist. In addition, the number of occurrences recorded for *M. rubida* significantly increased during the last two decades (Fig. 1). This coincides with the launches of GBIF and iNaturalist and likely indicates that more amateur naturalists added data to these platforms. Overall, the use of such platforms denotes an increase in public interest in ants and research (McKinley et al., 2017). This is corroborated by a recent study that revealed that in spring and during warmer months, more people use the keyword "ants" to search the internet (Queiroz et al., 2021). The increase in occurrences reported for *M. rubida* and many other species is most likely due to an increase in the interest of the amateur naturalists participating in online and citizen-science platforms, which has greatly increased over the last two decades (Bonney et al., 2015). Because the sampling of animal species is tedious, time-consuming and expensive (Wäldchen et al., 2018), this contribution is essential, as the data in citizen-science projects and platforms can be used in studies on conservation (McKinley et al., 2017; Maund et al., 2020). As reported here, 495 (81.0%) occurrences were obtained from online projects and platforms (e.g., GBIF, iNaturalist, BinsBoldSystem) compared with 166 (19.0%) from the literature and a field survey. It is important to note that 78 out of 166 occurrences were obtained from online literature and checklist searches. The searches were not exhaustive and additional occurrences may be found in local (online or printed) papers and checklists that are not available online or are not in English. Thus, it is important to use several strategies (e.g., use several search engines in several languages, ask colleagues), which are likely to yield additional records.

This study corroborates the importance of data gathered by the public, which is also supported by other studies. For example, a recent study confirmed that the ponerine ant *C. ochracea* is more abundant in Hungary than previously assumed (Báthori et al., 2022). This study used images of *C. ochracea* taken by amateur naturalists and the identity was confirmed by the authors. In doing so, a large amount of research-grade data became available and these authors were able to state that *C. ochracea* is not as rare as previously assumed. Importantly, such freely-available data can be used for developing SDMs as reported here. Another example is a citizen-science study that used people to collect samples of the pavement ant *Tetramorium immigrans* (Zhang et al., 2019), which is invasive to the USA (Steiner et al., 2008; Flucher et al., 2021) and were used to determine the distribution and carry out a genetic analyses of this species (Zhang et al., 2019). These two studies illustrate the importance and applicability of citizen-science projects on ants and animals in general (Maund et al., 2020). Such projects indicate the great advantages of engaging with amateur naturalists and, more broadly, with the public (McKinley et al., 2017). Data resulting from citizen-science projects and online platforms are thus essential, among others, for developing conservation strategies (Hochachka et al., 2012; McKinley et al., 2017; Callaghan et al., 2021) and predicting areas potentially suitable for invasive species (Guillera-Arroita et al., 2015).

CONCLUSION

This study demonstrates the importance of online platforms and projects for producing maps of the distributions of species and for modelling. The occurrences were gathered from online platforms, literature and field surveys (conducted in Tyrol, Austria) and used to produce a map of the distribution and a SDM of the ant *M. rubida*. In total, 611 data points were obtained for Eurasia. Importantly, most occurrences were obtained from online platforms (e.g., GBIF, iNaturalist). This data is easy, to obtain and freely available. It can be used to develop SDMs for many (non-model) species and for an evaluation of the current distribution and potential risks and threats for such species in the future (Crall et al., 2015; van der Wal et al., 2015; Zulian et al., 2021). The map of the distribution developed revealed that the main area of distribution of *M. rubida* is in mountainous areas in the European Alps, Central Massif and Carpathians, but it also occurs in the Pindus Mountains and Caucasus. The SDM indicates that there are areas of potentially suitable habitat for *M. rubida* in the Pyrenees, Apennines, European Uplands, Dinaric Alps, Carpathians, Pindus Mountains, Balkan Mountains, Pontic Mountains and Caucasus. The map of its distribution and the SDM indicate that *M. rubida* is not imminently faced with a threat of habitat loss. Nevertheless, with ongoing climate change (e.g. increase in drought events) and the advent of *F. fuscocinerea*, *M. rubida* may lose suitable habitat and move upwards in mountains. Thus, it is important to continue monitoring this species. Moreover, the methods described here can also be easily used to produce maps of the distributions and models for other species (see R script in the supplementary material and also Kass et al., 2018). This may be of interest for researchers studying non-model species because, often, there are no maps of their distributions or models for such species available. SDMs such as the one developed in this study enable to assess the current status of a species and the potential effect of climate change. Thus, data from online projects and platforms are essential for assessing the effect of climate change on animals and plants (McKinley et al., 2017) and planning conservation strategies (Foden et al., 2019; Ferraz et al., 2021).

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DATA AND CODE AVAILABILITY. The dataset generated for this study and the R-code used can be found in the supplementary material.

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Table S1. Number of occurrences recorded each year.

Years	Counts	Years	Counts
1932	1	2009	13
1933	1	2010	23
1936	1	2011	10
1940	1	2012	11
1949	1	2013	11
1950	2	2014	22
1952	1	2015	11
1953	1	2016	11
1954	1	2017	14
1957	2	2018	48
1958	1	2019	18
1976	1	2020	60
1978	1	2021	72
1980	1	2022	103
1982	1		
1987	3		
1988	1		
1991	3		
1992	3		
1993	2		
1994	1		
1997	1		
1998	1		
1999	2		
2000	2		
2001	6		
2002	12		
2003	3		
2004	17		
2005	12		
2006	2		
2007	8		
2008	11		

Table S2. The results of the statistical analyses of the 20 models.

FC	RM	Mean AUC value	10-percentile omission rate	AICc	delta AICc	Number of coefficients
L	1	0.944	0.104	10297.82	461.85	14
LQ	1	0.958	0.106	9915.63	79.66	25
LQH	1	0.961	0.119	9835.98	0.00	62
H	1	0.960	0.119	9860.01	24.03	61
L	2	0.941	0.106	10341.79	505.82	11
LQ	2	0.956	0.108	9981.50	145.52	22
LQH	2	0.959	0.117	9859.97	243.00	39
H	2	0.959	0.119	9895.61	59.63	43
L	3	0.941	0.099	10349.77	513.80	9
LQ	3	0.955	0.110	10023.69	187.72	19
LQH	3	0.957	0.112	9898.65	62.68	30
H	3	0.956	0.108	9926.00	90.03	33
L	4	0.940	0.099	10356.51	520.54	8
LQ	4	0.954	0.110	10046.68	210.71	15
LQH	4	0.955	0.115	9937.21	101.23	26
H	4	0.955	0.110	9954.99	119.02	27
L	5	0.939	0.099	10369.47	533.50	9
LQ	5	0.952	0.106	10070.54	234.57	13
LQH	5	0.954	0.108	9969.12	133.15	23
H	5	0.954	0.110	9992.05	156.08	31

Note: FCs – feature classe s. “L,” “Q,” and “H” – “linear”, “quadratic,” and “hinge” feature classess, respectively. RM – regularization multiplier. AICc – Akaike information criterion for small sample size. delta AICc – the difference in AICc score between the best model and the model being compared. The coloured cell denotes the best model based on AUC, AICc and deltaAICc.

Table S3. Statistical comparison of the empirical and null model in terms of the AUC and 10-percentile omission rate.

	Mean value of the empirical model	Mean value of the null model	Z score	p-value
AUC	0.96	0.59	12.50	<0.001
10-percentile omission rate	0.12	0.20	–1.99	0.023

The comparison of the empirical and null model was used to assess whether the empirical model fits the occurrence data significantly better than a model based randomly drawn occurrences. AUC – area under the curve. Coloured cells indicate altitudinal ranges with statistically significant higher numbers of occurrences.