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RESEARCH ARTICLE

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Assessing extinction risk across the geographic ranges of plant species in Europe

Hanna Holz[1] | Josiane Segar[1,2] | Jose Valdez[1,2] | Ingmar R. Staude[1,2,3]

[1]Institute of Biology, Martin Luther University Halle-Wittenberg, Halle (Saale), Germany

[2]German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena Leipzig, Leipzig, Germany

[3]Institute of Biology, Leipzig University, Leipzig, Germany

Correspondence
Ingmar R. Staude, Institute of Biology, Leipzig University, Leipzig, Germany.
Email: ingmar.staude@idiv.de

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Societal Impact Statement

Plants play fundamental roles in ecosystems, yet merely 10% of species have an assessment of their global extinction risk. Through the integration of national Red Lists and comprehensive global plant distribution data, we identify previously unassessed plant species in Europe that are threatened throughout their geographic range and thus at risk of global extinction. Our workflow can be replicated to facilitate the integration of disparate national monitoring efforts around the world and help accelerate global plant risk assessments.

Summary

- A comprehensive extinction risk assessment for plant species is a global biodiversity target. However, currently, only 10% of plant diversity is assessed in the global Red List of Threatened Species. To guide conservation and restoration actions in times of accelerated species extinction, plant risk assessments must be expedited.
- Here, we examine the extinction risk of vascular plant species in Europe through the integration of two data streams: (1) national Red Lists and (2) global plant distribution data from Kew's Plants of the World Online database. For each species listed on a national Red List, we create a list of countries that form part of its range and indicate the threat status in these countries, allowing us to calculate the percentage of the range in which a given species is listed as threatened.
- We find that 7% to 9% of European vascular plant diversity is threatened in its entire range, the majority of which are single-country endemics. Of these globally threatened species, 84% currently have no assessment in the global Red List.
- With increasing national biodiversity monitoring commitments shaping the post-2020 policy environment, we anticipate that integrating national Red Lists with global plant distribution data is a scalable workflow that can help accelerate global risk assessments of plants.

KEYWORDS
extinction risk assessment, national Red List, plant conservation, Plants of the World Online, threatened species

1 | INTRODUCTION

Loss of plant diversity is detrimental not only to humans and other organisms but also a threat to the health of ecosystems and the services they provide (Diaz et al., 2006; Mace et al., 2012; Molina-Venegas et al., 2021; Pereira et al., 2010). It is estimated that approximately 20% to 39% of plant diversity is currently at risk of extinction (Bachman et al., 2018; Brummitt et al., 2015; Nic Lughadha et al., 2020), with roughly 600 species extinctions in the last 250 years (Humphreys et al., 2019). Estimating the threat status of plants is a critical component of conservation planning yet is often subject to great uncertainty due to large assessment gaps and failures to coordinate national and global biodiversity monitoring systems (Navarro et al., 2017). For plants, only 10% of species have been globally assessed for extinction risk and listed in the International Union for Conservation of Nature (IUCN) Red List (Nic Lughadha et al., 2020). Establishing a tentative global list of threatened plant species is a key biodiversity target (Goal 2 of the Global Strategy for Plant Conservation [GSPC]); however, efforts have so far failed to meet this goal. To guide conservation management and government policy, extinction risk assessments for plants urgently need to be expanded.

Owing in part to the Convention on Biological Diversity's (CBD's) call for an "assessment of the conservation status of all known plant species" by 2020 (CBD, 2012), national efforts to assess the extinction risk of plant species have intensified during the last decade (Bachman et al., 2018; Nic Lughadha et al., 2020; Paton & Lughadha, 2011). These efforts have resulted in regional assessments for many thousands of plant species that have been published in national or regional Red Lists (Bachman et al., 2018). Such conservation assessments at the regional level can make an important contribution to global assessments for two reasons. First, if species are endemic to the region covered by the assessment, this corresponds to a global assessment (Bachman et al., 2018). Second, when national assessments are available for all regions of a species' native range, they can be integrated to assess their global extinction risk. Yet national Red Lists often do not capture the endemism status of listed species (IUCN, 2012). Additionally, accurate data on species geographic ranges remain far from comprehensive, despite substantial recent efforts to improve them. As a result, single-country endemics are underrepresented in the IUCN Red List (Nic Lughadha et al., 2020) and integration of national Red Lists across species ranges to assess global extinction risk has been hampered.

In order to fill this data gap, the recent Plants of the World Online (POWO) database (https://powo.science.kew.org/) has attempted to obtain data on the global geographic distribution of nearly all accepted vascular plant species. Since its inception, it has been continuously updated with newly published data and reviewed by experts. Linked with the World Checklist of Vascular Plants (WCVP; http://wcvp.science.kew.org/), the dataset contains about 1.4 million plant names of which 345,000 are accepted species (Govaerts et al., 2021). Accepted species are associated with distribution data following the international standard of the World Geographical Scheme for Recording Plant Distributions (WGSRPD; Brummitt et al., 2001). Approximately two million WGSRPD Level-3 areas (henceforth referred to botanical countries; Brummitt et al., 2001) are associated with scientifically accepted species names (POWO, 2021). These global plant distribution data represent a new opportunity for global change ecology, and its application may help accelerate the pace of plant conservation science. One such application is integrating national Red Lists with the global distribution data to assess extinction risk across the geographic ranges of species and fill the gaps in global threat assessments of plants.

Here, we combine the two data streams above and integrate the most recent national Red Lists from across Europe (Figure 1) to assess where species are threatened within their geographic range. The last European Red List of vascular plants was compiled a decade ago (Bilz et al., 2011) and focused primarily on policy species (i.e., species listed in European or international policy instruments, such as the Habitats Directive) and therefore covered only a specific subset of the European flora (but see Allen et al., 2014; Rivers et al., 2019; and IUCN, 2019 for more recent, complementary lists on medicinal plants, trees, and selected shrubs, respectively). Here, we present a scalable workflow for an updated and comprehensive European plant risk assessment. The main objectives of this study are to establish a preliminary list of threatened European species, the countries where they occur, and the countries where they are listed as threatened, so that we can assess in how many countries a species is threatened and whether it is threatened throughout its range, that is, at risk of global extinction. We hope that the workflow presented here can serve as a starting point for integrating national monitoring efforts to accelerate the compilation of a global database of threatened plant species.

2 | METHODS

2.1 | Synthesis of Red Lists

We coalesced the most recently published national Red Lists from 37 countries in Europe (Table S1). The geographical coverage of these Red Lists extends from Portugal in the west to Romania in the east and from Norway in the north to Cyprus in the south (Figure 1a). The only countries where Red Lists were not yet available were Scotland, North Macedonia, and Serbia. Some countries had more than one Red List (e.g., Italy has a separate Red List for policy species, endemic species, and all other species), totaling in 41 national Red Lists for the 37 countries (Table S1). In such cases, we combined the Red Lists per country and removed species duplicates. We extracted species names and their threat status from national Red Lists. Threat classifications followed IUCN Red List criteria in 36 out of the 41 national Red Lists; five lists had national threat classifications, which were translated to the IUCN system by consulting the description of the categories given in the respective Red Lists (Table S2). We only considered species listed as threatened or extinct as many plant species are rediscovered after extinction (Abeli et al., 2021; Humphreys et al., 2019). Thus, we included the following IUCN categories: VU (Vulnerable), EN (Endangered), CR (Critically Endangered), RE (Regionally Extinct), EW

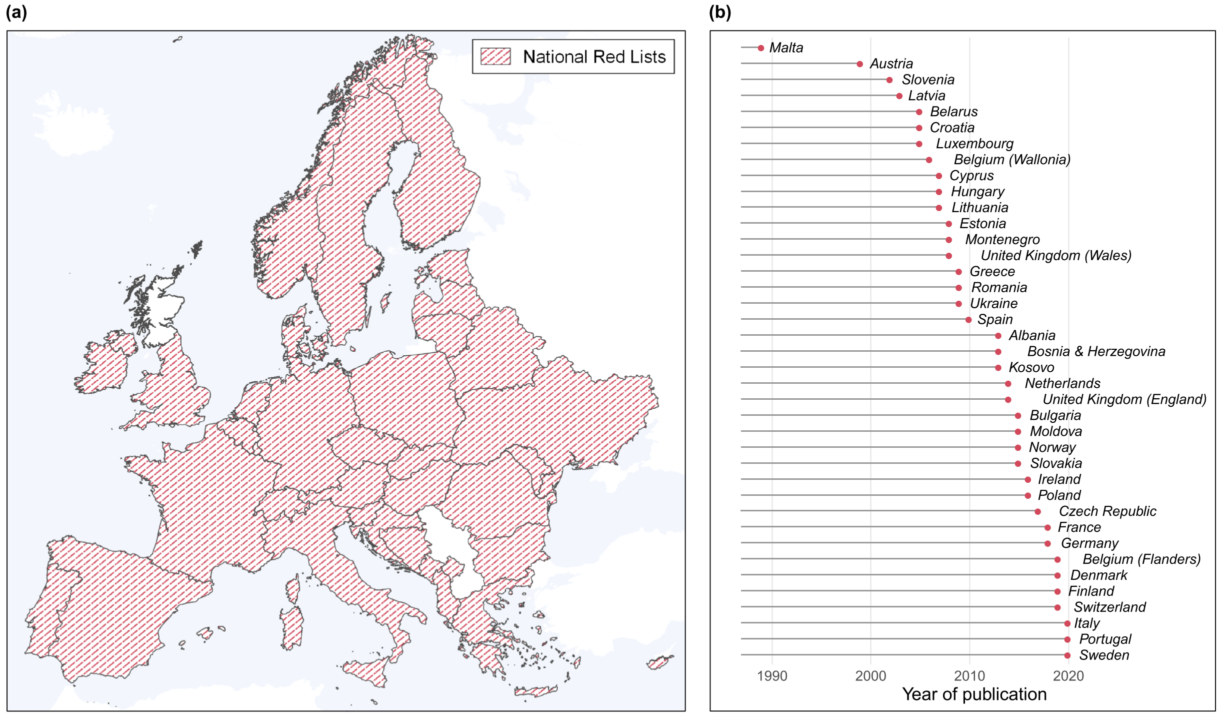

FIGURE 1 National Red Lists were available for 37 countries in Europe, with 2013 as the median publishing year. (a) Map of Europe with political countries (black outline) for which national Red Lists were available (fill in red dash). National Red Lists were matched to botanical countries (i.e., WGSRPD Level-3). See Table S3 for a crosswalk between political and botanical countries. (b) Year of publication of national Red Lists. National Red Lists were not available for Scotland, North Macedonia, and Serbia

(Extinct in the Wild), and EX (Extinct). We used the backbone taxonomy of the Global Biodiversity Information Facility (GBIF) and the R packages rgbif (Chamberlain et al., 2021) and taxize (Chamberlain et al., 2020) for fuzzy matching, standardization, and harmonization of species names among national Red Lists (see harmonization code on GitHub: 01_harmonization.R). We only included accepted vascular plant species. In total, our database comprised 7192 accepted species of vascular plants.

2.2 | Integration with geographic data

We used Kew's POWO database to identify the geographic distribution for each of the 7192 threatened species in our database. The backbone taxonomy of POWO is based on the WCVP, which lists the known synonyms for each accepted species. This allowed us to match species names, even if species in our database were not accepted in POWO. For 97% of the species in our database, we could find the geographic distribution. Additionally, because POWO lists WGSRPD Level-3 areas, instead of recording species distributions at the scale of political countries, we regrouped national Red Lists according to botanical countries. For instance, we combined the national Red Lists of the Czech Republic and Slovakia into one list for Czechoslovakia (see Table S3 for all regroupings). We then matched all species distribution data from POWO with our Red List database, so that the resulting data frame indicates for each species all countries where a species occurs and whether it is threatened or nonthreatened in a given country. Finally, POWO also allowed us to calculate the number of species native to a botanical country. We used these numbers to estimate the taxonomic coverage of national Red Lists. For this, we divided the number of assessed species (also including nonthreatened species) per botanical country by the number of species in that botanical country (Figure S1 and Table S4).

2.3 | Extinction risk assessment

We used our combined database to count for each species the number of botanical countries in which it is listed as threatened. Next, we assessed a species extinction risk across its range by quantifying the ratio between the number of countries where a species is threatened and the number of countries where a species occurs. To give greater weight to threat status in larger countries (i.e., a species may deserve greater attention if it is threatened in three large, rather than three small countries), we calculated an additional metric that accounted for area. For this, we divided the summed area of countries in which a species is listed as threatened by the summed area of countries in which the species occurs. We were unable to quantify these ratios for species whose ranges extend outside Europe into countries for which we did not compile national Red Lists. Therefore, we confined our subsequent analysis to species that have their range exclusively in Europe. For these species, we quantified their range-wide extinction risk. For species that were threatened in 100% of their range, we asked whether they are listed in the IUCN Global Red List, and if so, under which categories. Finally, we determined which genera and families contained the highest number of threatened species and in which countries most of these species occur. All data and R code are available on GitHub at https://github.com/istaude/european_redlist_synthesis. An overview of the workflow above with relevant data and R code files is presented in Figure 2.

3 | RESULTS

The median publication year of the most recent national Red Lists across 37 countries in Europe was 2013 (Figure 1b and Table S1), and the median taxonomic coverage (i.e., percentage of species assessed in the total native flora of a botanical country) was 41% (mean = 53%; Figure S1). Synthesizing these lists revealed that 28% to 35% (6987 out of an estimated 20,000–25,000 species; Bilz et al., 2011; POWO, 2021) of the European vascular plant flora are listed as threatened in at least one botanical country (Figure 3a). A clear majority of species is threatened in one to five botanical countries (approximately 90%); only two species are threatened in 20 or more countries (e.g., *Herminium monorchis* in 20 countries and *Botrychium matricariifolium* in 21 countries; Figure 3b). However, even species that are threatened in only a few countries may be at risk of global extinction if their distribution is restricted to those countries (e.g., *Achillea thracica*; Figure 3c). By contrast, many species threatened across Europe can have large parts of their range outside of Europe for which our database does not contain assessments (e.g., *H. monorchis*), preventing us from evaluating these species' global threat status.

Combining our Red List database with species distribution data, we identified nearly half (46.97%) of the species in our database (3282 species) as endemic to Europe. For these species, we found that 15%, 26%, 3%, and 56% of species were threatened in 0% to 25%, 25% to 50%, 50% to 75%, and 75% to 100% of the countries in which they occur, respectively (Figure 4a). When considering country area, 19%, 14%, 7%, and 60% of species were threatened in up to 0% to 25%, 25% to 50%, 50% to 75%, and 75% to 100% of their distributional range, respectively (Figure 4a). A total of 1842 species were listed as threatened in 100% of their distribution, presenting 7% to 9% of Europe's vascular plant diversity at risk of global extinction (Figure 4c). The majority (95%) of these species were single-country endemics, with only 79 species globally threatened in multiple countries (67, 9, 2, and 1 species in 2, 3, 4, and 5 countries, respectively).

We found that 84% of the species identified as globally threatened in our analysis were either not evaluated (83%) or were data deficient (1%) on the IUCN Red List (Figure 4b). Furthermore, 1.6% of the globally threatened species were classified as being at lower risk (i.e., Least Concern, Near Threatened) in the IUCN Red List. For example, *Ramonda serbica*, which occurs solely in Albania, Bulgaria, Greece, and Yugoslavia and is classified as Vulnerable/Endangered in these

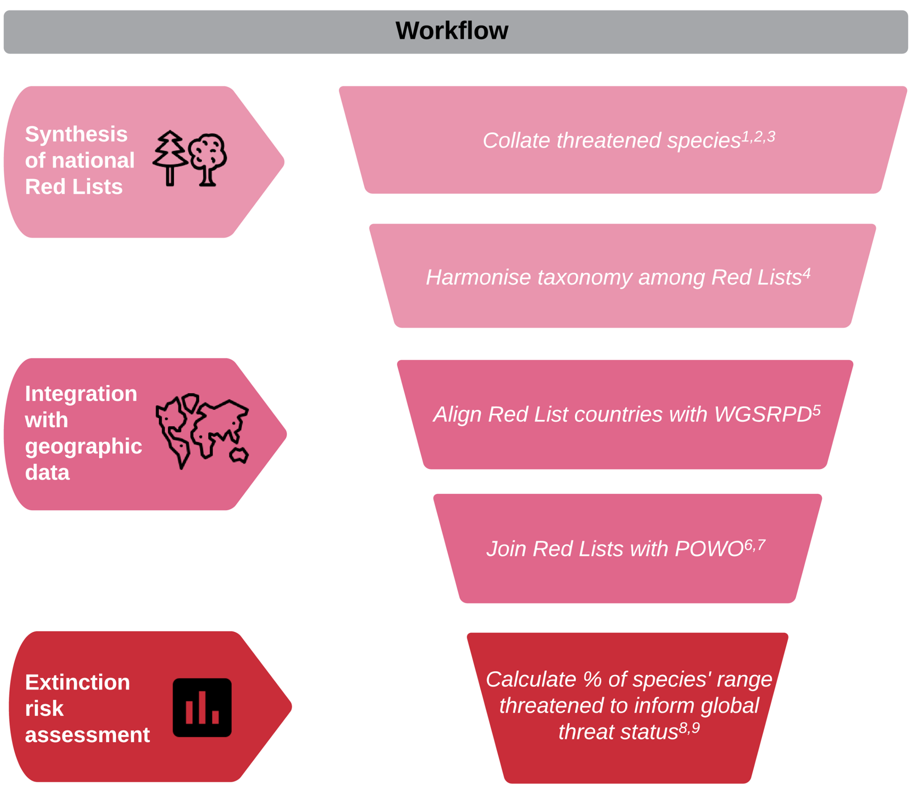

FIGURE 2 Workflow of integrating national Red Lists to inform global risk assessments. Footnotes indicate relevant R code and data outputs: [1]Table S1 for bibliography; [2]Table S2 for threat categories; [3]redlist_clean.csv; [4]02_rlharmonization.R; [5]Table S3 for crosswalk; [6]05_redlist_kew_merge.R; [7]rlspecies_distribution.csv; [8]rlspecies_percentage_threatened.csv; [9]icun_rl.csv. All CSV files and R code are available on GitHub at https://github.com/istaude/european_redlist_synthesis

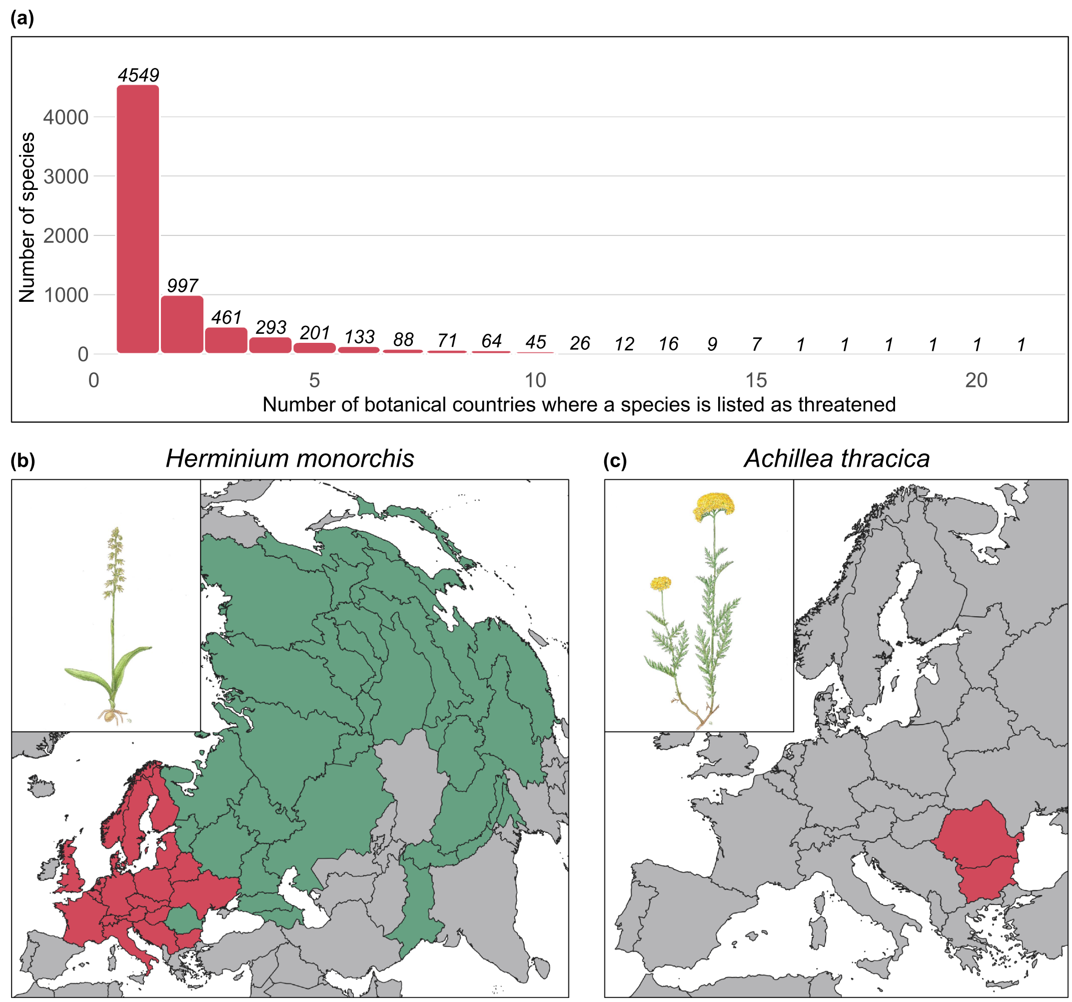

FIGURE 3 Six thousand nine hundred eighty-seven species of the 20,000–25,000 vascular plant species in Europe (i.e., 28% to 35%) are threatened in at least one botanical country. (a) The number of species against the number of botanical countries where they are listed as threatened. (b) Although *Herminium monorchis* is threatened in 20 countries (colored in red), its distribution is wide and ranges far beyond Europe, for which our database does not include Red Lists (colored in green). (c) *Achillea thracica* is threatened in only two countries (Romania: Critically Endangered and Bulgaria: Vulnerable) but is endemic to these two countries and therefore at risk of global extinction. Credit for inset drawings: Dimitar Vlaev in Peev et al., 2015

countries, is listed as Least Concern by the IUCN. Only 14% of the species were also classified as threatened by IUCN (i.e., listed as Critically Endangered, Endangered, or Vulnerable). A total of 0.3% of species were classified as extinct by the IUCN (e.g., *Viola cryana*, an endemic species in France).

Globally threatened species (i.e., threatened in their entire range) were overrepresented in Mediterranean countries (Figure 5a and Table S4). Spain had the most species threatened with global extinction ($n = 578$; 31%), and Italy and Greece had 233 and 156 species, respectively. Outside of the Mediterranean region, Sweden had the most threatened species ($n = 332$), followed by England ($n = 101$). The country with the lowest number of threatened species was Finland ($n = 1$). In total, threatened species distributed over 360 genera. The three plant genera with the highest number of species threatened were *Hieracium* (Asteracea), *Limonium* (Plumbaginaceae), and *Centaurea* (Asteracea) (Figure 5b). Together, these three genera accounted for a third (33%) of the European species that are at risk of extinction.

4 | DISCUSSION

Here, we provide insight into the threat status of vascular plant species through the compilation and analysis of the most recent national Red Lists across Europe. We found that nearly 7000 or approximately a third of all vascular plant species occurring in Europe are threatened in at least one botanical country. Nearly half of these threatened species are geographically restricted to Europe, where we find that 7% to 9% of vascular plant species in Europe are threatened throughout their entire range, most of which are species endemic to a single

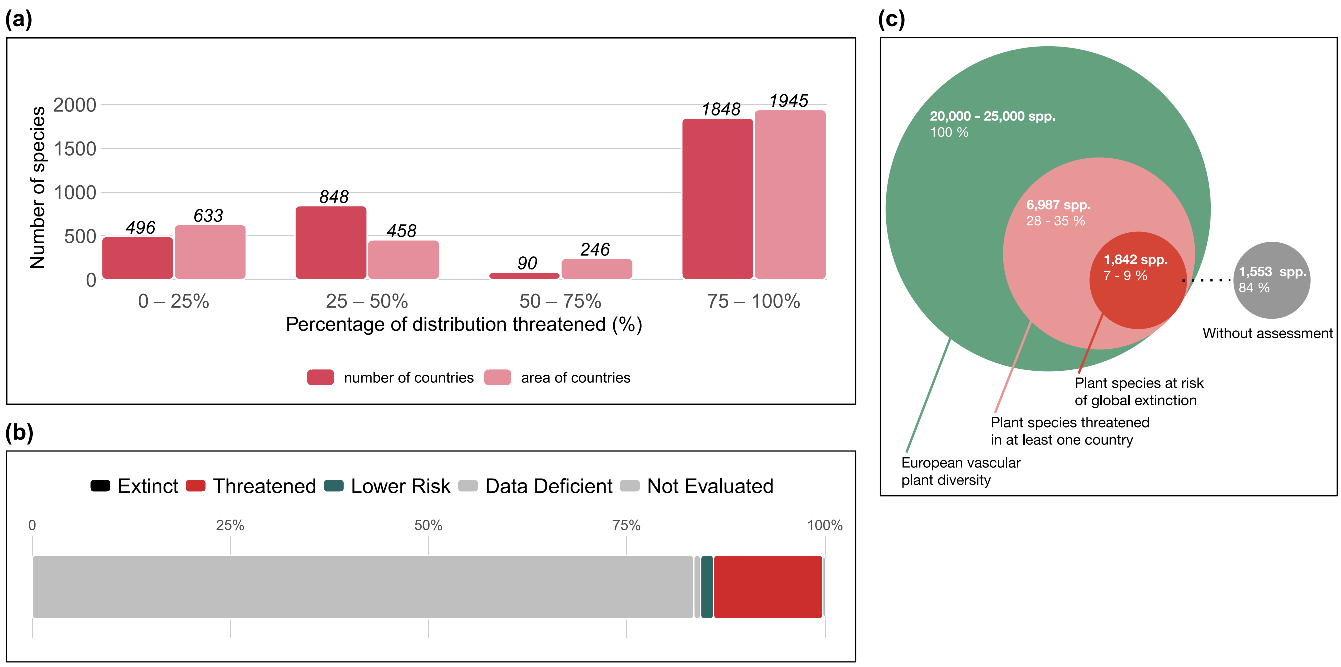

FIGURE 4 Between 7% and 9% of all European vascular plant species are at risk of global extinction, with 84% of these species lacking an IUCN assessment. (a) The number of species endemic to Europe and the percentage of their distribution where they are threatened. Percentages refer to the ratio between the number of countries where a species is threatened and the number of countries where the species occurs (dark red), and the ratio between the summed area of countries in which a species is threatened and the summed area of countries in which the species occurs (light red). (b) Species threat status in the IUCN Red List of all species identified as globally threatened in our analysis (i.e., threatened in 100% of their distribution). (c) Nested proportional area chart summarizing key figures for threat and assessment status from our analysis

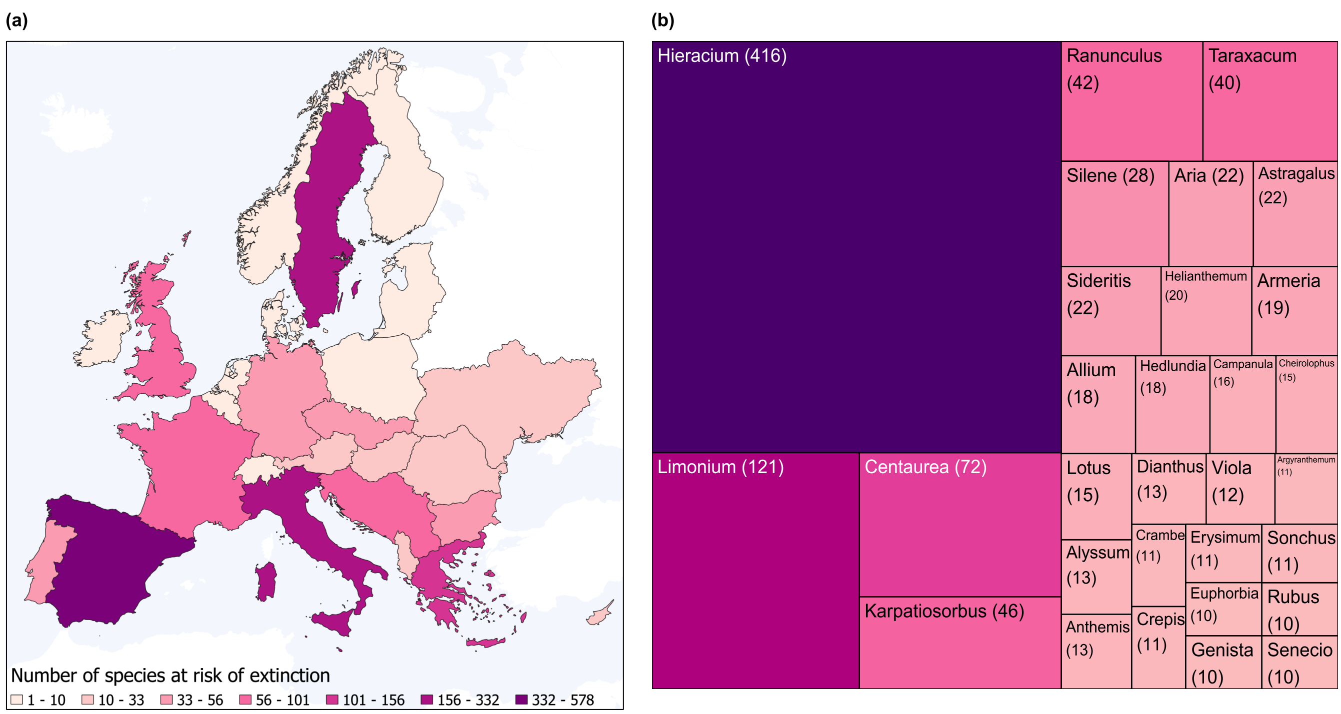

FIGURE 5 Geographic and taxonomic hotspots of species globally threatened. (a) Map of the number of species threatened in 100% of their range (i.e., globally threatened) per botanical country. (b) Treemap of the number of globally threatened species per genus. The size of the rectangles is proportional to the number of threatened species. Genera with fewer than 10 globally threatened species were excluded from the figure

country. Of these globally threatened species, 84% were missing from global IUCN Red List assessments. Our synthesis highlights the mismatch between global and regional efforts in extinction risk assessments, the urgent need for the inclusion of national-level assessments for endemic species in the IUCN Red List, and how disparate national monitoring efforts could be integrated to help accelerate global risk assessments of vascular plants.

Our estimate of threat status (i.e., 7% to 9% at risk of global extinction) is lower than other estimates in the literature. Yet comparison among estimates is challenging. The European Red List of Vascular Plants from 2011, for example, identified 25% of their 1826 assessed species as being threatened with extinction, with an even higher percentage for policy-only species: 44.9% Europe wide and 47% across EU27 countries (Bilz et al., 2011). Because policy species are often already endangered, these estimates are likely to be biased, and therefore, extrapolation from these values to all vascular plants in Europe may overestimate the overall threat status. Other studies at the global level found that as many as 30% to 39% of assessed plant species are threatened with extinction, while only 8% are at risk of extinction when comparing the number of threatened species to global plant diversity (Bachman et al., 2018; Nic Lughadha et al., 2020). The latter estimate is methodologically and numerically close to our estimate. Nonetheless, because most of the threatened species in these analyses are single-country endemics (Bachman et al., 2018; Nic Lughadha et al., 2020), most of which occur in biodiversity hotspots and in highly diverse regions often outside of Europe (Joppa et al., 2011; Myers et al., 2000), the geographic extent of these studies makes it difficult to reliably compare these estimates.

Although our assessment is based on a comprehensive synthesis of national Red Lists, our estimate of overall extinction risk is subject to limitations. First, we did not include species with ranges outside Europe. We therefore miss species that are threatened both inside and outside of Europe. Second, national Red Lists do not cover all plants occurring in a given country (median 41%, see Table S4). Thus, one country may have listed a species as threatened, while another country has yet to assess the same species, with some potentially threatened species having not been assessed at all. Our overall extinction risk estimate is therefore likely conservative. However, both of these limitations may be overcome by increased national monitoring efforts in the post-2020 policy environment (CBD, 2021; Sharrock, 2020) and by global integration of national Red Lists. A third limitation is the spatial mismatch between national Red Lists (i.e., at the political country level) and species distribution data (i.e., at the botanical country level). Because the spatial extent of a Red List assessment influences the extinction risk of a species (Keil et al., 2018), we suggest that, particularly for larger political countries, Red List assessments be conducted at the typically smaller botanical country level (Brummitt et al., 2001). This could greatly facilitate the integration of monitoring efforts with species distribution data and help provide more reliable estimates of overall extinction risk.

Our analysis also allowed us to determine where threat hotspots are located in Europe and whether some genera have particularly high numbers of threatened species. As expected, threat regions were concentrated in Mediterranean countries, which are known hotspots of biodiversity and endemism (Myers et al., 2000). Unexpectedly, Sweden also had a high number of globally threatened species, suggesting a high rate of endemism for which, to our knowledge, no evidence has yet been published and we call for expert validation. The species threatened in Sweden belonged mainly to the genus *Hieracium* (316 out of 322 species). In Greece, *Hieracium* also greatly contributed to globally threatened species, with its distribution over lowland and coastal habitat being under substantial pressure from land-use change (Kougioumoutzis et al., 2021). The concentration of threatened species in three genera (i.e., *Hieracium*, *Limonium*, and *Centaurea* accounted for 33% of threatened species) suggests extinction risk may be phylogenetically clustered (Davies, 2019; Molina-Venegas et al., 2020; Tanentzap et al., 2020). Although we do not examine drivers of extinction risk, we note that three of the most threatened genera *Hieracium*, *Limonium*, and *Karpatiosorbus* reproduce by apomixis, cloning through seeds (see Figure S2 for geographic hotspots when apomictic genera are excluded). Apomixis is usually associated with rapid speciation rates and with rapid extinction rates (Koutroumpa et al., 2021). This suggests, in addition to focusing on external factors, intrinsic factors of species life history, particularly with respect to reproduction, and lineage diversification history may be key to understanding extinction patterns (Davies et al., 2011).

Our finding that 84% of globally threatened species in Europe have no IUCN Red List assessment mirrors the overall low coverage (i.e., 10%) for vascular plants and echoes previous studies indicating large assessment gaps in this list (Bachman et al., 2018; Nic Lughadha et al., 2020). We found that a particularly large number of globally threatened but unassessed species are single-country endemics. The inclusion of national-level assessments of single-country endemics in the IUCN Red List remains a priority (with initiatives underway for some countries, e.g., South Africa, Brazil, and Lebanon, but not yet for Europe), and we urge that more resources be made available to facilitate the listing of these species by the IUCN. However, given this continual, systematic lack of inclusion, our approach could provisionally address this shortcoming by identifying and synthesizing threatened, single-country endemics from national Red Lists in a relatively straightforward manner. Moreover, we note some discrepancies between our globally threatened status and that of the IUCN. For example, in the case of *R. serbica*, expert assessors found, in contrast to our assessment, that the available data did not allow for any of the IUCN Red List thresholds for classification as globally threatened. We therefore suggest that if expert assessments are available at the global scale, these should be prioritized, whereas our approach could serve as an assessment prioritization tool highlighting species that require evaluation and as a tentative indicator for species extinction risk in the absence of expert assessments. In these ways, integrating national Red Lists across species geographic ranges could help expedite global extinction risk assessments for plants.

To further fill the large gaps in global assessments while leveraging regional efforts in extinction risk assessment, nations worldwide need to establish, update, and integrate their Red Lists. An online platform for decentralized uploads of national Red Lists, taxonomic harmonization, and integration with the geographic distribution of species could be established. The recently launched GlobalTree Portal (http://bgci.org/resources/bgci-databases/globaltree-portal) is an example of how something similar has been achieved for the world's trees. Existing platforms such as National Red List (http://nationalredlist.org/) or ThreatSearch (https://tools.bgci.org/threat_search.php) could be extended to help achieve this goal on a broader basis for all vascular plants but will require more funding to ensure updates, smooth operation, and high utility. Future applications could further visualize for each species where in its range it is threatened and the causes for its decline, providing a much-needed synthesis for policy and conservation planning. The fraction of geographic units where a species is threatened could be calculated and fed into the IUCN global Red List. Regular updates of Red Lists could also result in dynamic maps of a species geographical threat status and allow the monitoring of conservation success, recovery actions and biodiversity trends. To bolster national Red Lists and shorten time spans between assessments, the recent upsurge of citizen science activities could be leveraged to inform temporal trends of species more regularly (Bowler et al., 2021). Taken together, such a process of data integration could enable better cross-national collaboration and coordination (Kühl et al., 2020), which could greatly accelerate extinction risk assessments globally.

Our synthesis of national Red Lists across Europe identified over 1500 globally threatened plant species that were not assessed by the IUCN, thereby not only highlighting but also filling a knowledge gap. We present a workflow for harnessing the increasing availability of national Red List assessments in the hope of providing a framework for similar undertakings in other regions. Finally, the dataset we present here could be useful for a variety of purposes, such as relating patterns in the geographic distribution of species threats to land use or climate warming, assessing whether conservation measures such as protected areas and ex situ conservation provide adequate coverage, or more generally identifying knowledge and data gaps (e.g., trait data) for threatened species. An easily accessible and globally complete database of threatened plant species will be instrumental in coordinating effective conservation planning and sharing efforts to bend the curve of biodiversity loss. The integration of national efforts with global datasets present a historically unique opportunity for coordinated global plant conservation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

IRS devised the study. HH and IRS collated data and performed analyses. HH, JS, and IRS produced figures. HH, JS, JV, and IRS wrote the manuscript. IRS supervised the project.

DATA AVAILABILITY STATEMENT

All data and R code are available on GitHub at https://github.com/istaude/european_redlist_synthesis.

ORCID

Hanna Holz https://orcid.org/0000-0003-4290-2064
Josiane Segar https://orcid.org/0000-0001-9481-7211
Jose Valdez https://orcid.org/0000-0003-2690-9952
Ingmar R. Staude https://orcid.org/0000-0003-2306-8780

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