www.nature.com/scientificdata

scientific data

OPEN

DATA DESCRIPTOR

Database of European vascular plants red lists as a contribution to more coherent plant conservation

Nina Lončarević *et al.*[#]

We introduce the database of European vascular plant red lists, a compilation of red list categories designated to taxa during in-country conservation assessments. Version 1.0 of the database is a standalone static dataset with open access in an end-user friendly format. Its aim is to fulfil the objectives of European Cooperation in Science and Technology (COST) Action 18201, ConservePlants. The database synthesizes data across 42 red lists from 41 countries, with participation of 39 out of a total of 44 European countries and two additional Mediterranean countries. The database contains 51,109 records representing 21,481 original taxonomic names with 37 different red list categories. During data harmonisation, 20,312 of the original taxonomic names were assigned to 17,873 unique accepted taxonomic names with scientific authorships across 184 families, 1650 genera and 15,593 species; and red list categories were standardised to 13 unique categories. We see this database as a source of information in diverse plant conservation activities and suitable for various stakeholders.

Background & summary

The European vascular flora is estimated at more than 20,000 species, with the highest diversity concentrated on the Iberian, Apennine and Balkan Peninsulas[1,2]. Although the European flora represents ~5.7% of the global plant diversity, 44.9% are estimated to be threatened with extinction within Europe[2] and this number is similar to the recent global level predictions for extinction risk[3]. One of the main aims of plant conservation is the evaluation of the extinction risk of each taxon through a conservation assessment and assigning a red list category to reflect its conservation status[4]. This process is widely referred to as threat assessment in determining the threat status. This framework was first established in 1964 by the International Union for Conservation of Nature and has become the globally accepted method for assessing the extinction risk of a taxon (IUCN, https://www.iucnredlist.org/about/background-history). Its guidelines are applied in conservation assessments at different geographical levels, but they all essentially aim to determine how close a taxon is to being extinct: global, continental, regional, national and sub-national. Globally, biodiversity is declining at an unprecedented rate, and conservation assessments have become the most important source of information to produce the Red List Index (RLI) used for monitoring the aggregated or overall extinction risk of taxa over time[5]. The index indicates a rate at which the taxa move towards or away from extinction risk. The IUCN uses a series of numerical thresholds, based on measurements of taxon abundance and decline, to assess the risk of extinction of a particular taxon and assign a conservation status using a red list category. The criteria rely on taxon data such as population size, trends in population growth, geographical distribution, and threats to the taxon or its habitats, etc[6]. There are 9–11 red list categories in the wider global to sub-national usage to identify how close a taxon is to extinction. Taxa in Critically Endangered (CR), Endangered (EN) and Vulnerable (VU) categories are collectively described as 'Threatened' with a high risk of extinction. Although most European countries used the IUCN standards for conservation assessments, this is not the case for all countries. Some relied on older versions of red list categories[7] (e.g., Malta – "Rare"), used criteria intended for global assessment and not for national level[8] or slightly adapted the existing categories or created entirely new categories (e.g., Slovenia - O1 as a subcategory of the old "Out of danger").

There are several inconsistencies in threat assessments between countries, hampering efforts to assess meaningful trends across countries or to create a unified list for Europe. Significant gaps exist in the availability

[#]A full list of authors and their affiliations appears at the end of the paper.

of biodiversity data among European countries which leave space for potential biases when prioritising conservation assessments[9]. Sometimes, national red list documents are difficult to access, being available only in national languages or printed in a limited number of hard copies that are unavailable digitally or online. National red lists are often tailored to local contexts, considering specific ecological, geographical, and socio-economic factors. As a result, there are different approaches to red listing, e.g., using IUCN criteria, developing their own-criteria, focussing on a limited number of taxa, etc[10]. Due to the dynamic nature of taxonomy, if the red list is older, it is more likely the listed taxonomic names are outdated and not reflect the current taxonomic concepts. Additionally, older red list assessments may no longer accurately reflect the current conservation status of taxa, especially those previously assessed through expert judgement or using outdated or opportunistic data, necessitating re-assessment. Consistent and continuous biodiversity data collection and monitoring are linked to strong economies, which can afford to invest in nature conservation[11]. Poorer economies, like countries of the Balkan Peninsula, harbour the most taxa-rich floras in Europe[12], but lack resources to support conservation assessments[13]. Economic differences further widen the gap due to lack of resources and in-country experts to conduct the red listing process[14]. In Europe, there are laws, policies, strategies, conservation reports, national action plans (e.g., EU Biodiversity Strategy, National Biodiversity Action plans, etc.) and country-level laws, but their successful implementation lags behind for most countries[15–17]. In the same context, red lists play a similar role, primarily serving as informative tools for conservation management practices, as they typically do not entail direct legal consequences[4]. The overall inconsistent and scattered commitments inevitably lead to considerable tardiness of critically important conservation measures.

With the simple but pertinent aim to improve plant conservation in Europe through a network of interested stakeholders, the European Cooperation in Science and Technology (COST) Action 18201 - 'An integrated approach to conservation of threatened plants for the 21st Century' (ConservePlants, https://www.conserveplants.eu/en/) was established in 2019. Within Working Group 3 (WG3) of ConservePlants, the main aim was to help fill the gaps in plant conservation by creating a unified list of red listed vascular plant taxa in Europe which have had a conservation assessment at country or sub-country level with their designated red list categories and presenting it in a user-friendly format as a database.

The objective of our work was to develop a database for European vascular plant red lists and make the data easily accessible and usable. Databases are becoming an increasingly necessary and more commonly used search tools to make sense of plant extinction risks, conservation efforts, and measures[18] (e.g., ThreatSearch database hosted by Botanic Gardens Conservation International, https://tools.bgci.org/threat_search.php). Whilst differences in human and financial resources and implementation of conservation policies remain ongoing challenges between regions in Europe, we envision such a database will be a pivotal tool to analyse and evaluate the status of plant conservation in Europe and will hence serve to fill some of the gaps in nature conservation.

Methods

We developed a stage-by-stage custom workflow, from data compilation to the final database product (Fig. 1). The static version of the main dataset and the accompanying technical validation dataset are both available via figshare repository (10.6084[19] and 10.6084[20]).

Data compilation. We targeted the most up-to-date original data sources (vascular plants red lists and red data books), as this increases data quality and robustness. These were either provided by COST Action members or gathered by lead authors directly. Most of the red lists were acquired from January to September 2021 and the process was concluded in March 2023. Data were compiled from original digital documents in pdf format, data extracts of originals as MS Excel spreadsheet or MS Word documents, URL/DOI for web pages, online databases or published articles, and hard copies of books, journals and reports. Data for some countries were compiled from multiple sources, as more recent published assessments were available but had not been included in the country's main red list (e.g., Italy, Ukraine, Lebanon) (Supplementary Table S1). We obtained a total of 42 red lists from 41 countries, with participation of 39 out of a total of 44 European countries[21–70]. Two additional countries were COST Action observers from the Mediterranean, Israel and Lebanon. Belgium does not have a national red list but has provided two red lists for Flanders and Wallonia regions, which together cover the entire country. The red list of Ireland covered the flora of the entire island as a single biogeographic unit. For some European countries, the red lists are either absent, include a handful of taxa, or only partially represents a country's geographic range. For example: Bosnia and Herzegovina (BiH) has a partial red list, including the Federation of BiH, but not Republika Srpska; Montenegro does not have a red list, Serbia's red book only included taxa of CR, Regionally Extinct (REX) and Regionally Extinct in the Wild (REW) red list categories and North Macedonia is in the process of preparing a red list, and had a very small number of taxa assessed, hence we did not include it (Fig. 2). From the red book of Serbia, produced in 1999, we removed taxa belonging to the Republic of Kosovo, which separated from Serbia in 2008. Taxa removed from Serbia's red list were not added to the Republic of Kosovo red list[37]. We used common ontology when describing plant taxonomy or data related to conservation assessments. The red lists consist of varying information. Some are only listed with a taxonomic name (genus level and beyond) and a red list category. Taxonomic names in some are listed with scientific authorships and higher taxonomic levels such as Family, Order, Class, etc. The red list categories have substantial variation among countries, with a total of 37 categories adopted by individual countries besides the official IUCN categories (Supplementary Table S2). Several countries used IUCN national red listing categories. Some countries devised their own categories (e.g., Latvia, Germany), used outdated IUCN categories (e.g., Romania, Slovenia, Malta), modified old or new IUCN categories to fit the country's objectives (e.g., Slovenia). Nowadays, there is an unspoken consensus on the use of the IUCN red listing system as the key authority in this field. The differences we observed in conservation assessments were mainly associated with the publication date of a red list - some were produced twenty and more

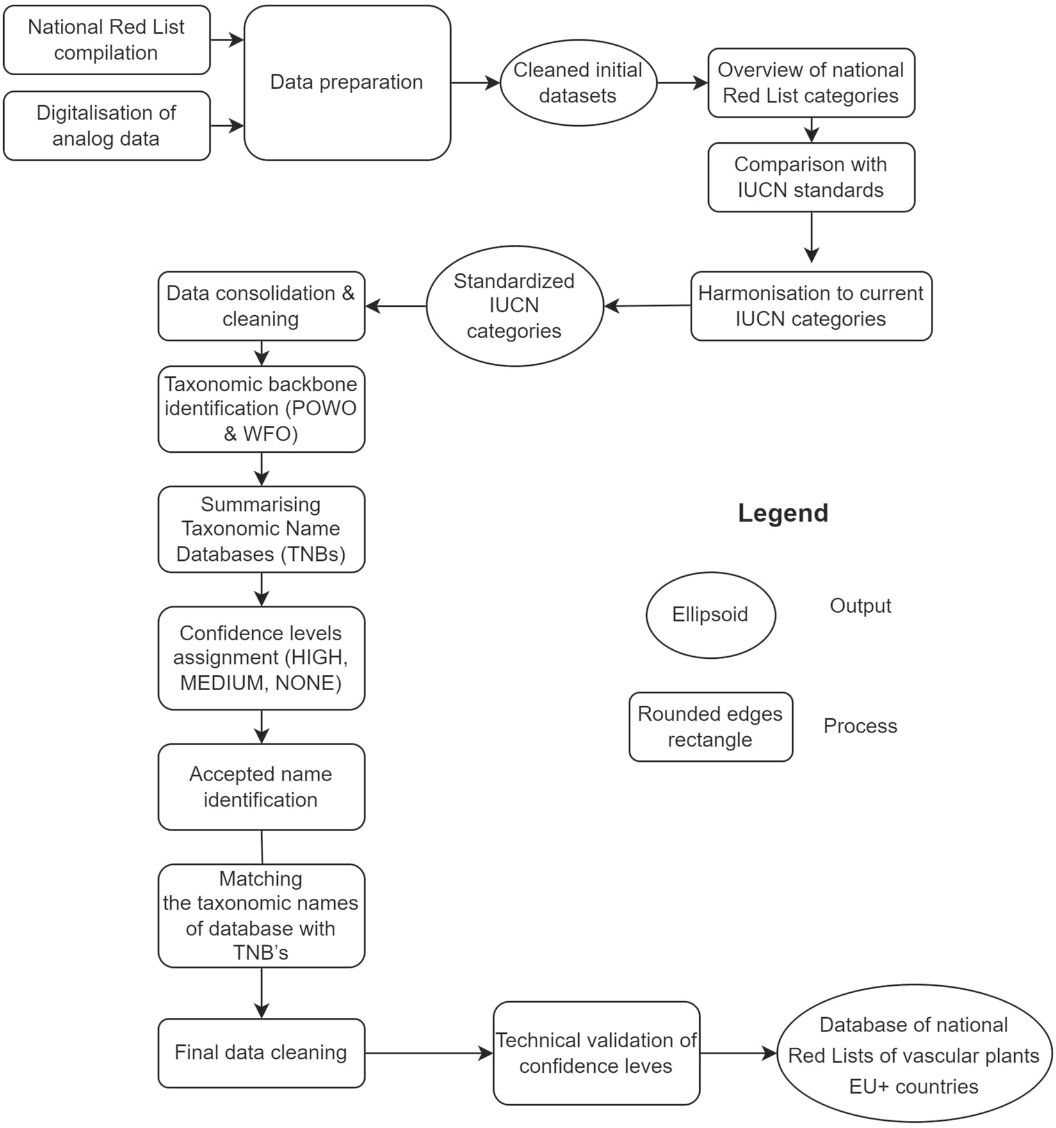

Fig. 1 Custom workflow of database development. Ellipsoids show the output while rounded edges rectangles show processes of our database creation. Abbreviations: Plants of the World Online (POWO), World Flora Online (WFO), Taxonomic name backbone (TNB), International Union for Nature Conservation (IUCN).

years ago – when a consensus on red listing and the strict adherence to assessment using IUCN criteria was not yet established.

Data preparation. The data compiled from sources (red lists, books, etc.) were regarded as original, and any subsequent changes, like data cleaning either to improve accuracy or data harmonizing, were treated as revisions. Data preparation, for each country, involved transforming data extracted from sources (Supplementary Table S1) into Microsoft Excel[71] spreadsheets and a rapid session of data cleaning to correct obvious mistakes in spellings and taxonomic abbreviations. Each spreadsheet had two columns of data. The first column captured the taxonomic name from genus to infraspecific epithet level. We excluded taxonomic names that are listed without a red list category; taxonomic levels below the infraspecific epithet (e.g., text in bold is removed, *Scilla bifolia* subsp. *spetana* **var**. ***magnomoravica***); artificial hybrids of two distinct genera or intergeneric hybrids; aggregate or closely-related taxa that are challenging to distinguish into singular taxon and kept together for practical purposes; taxa that are described in a broad sense (e.g., *sensu lato*); some taxonomic ranks below the genus, but above the species level (e.g., Section); genera without species epithets (e.g., *Orchis* sp. or *Orchis* spp.); duplicated taxa, where the duplicate has the same or lower red list category (we opted to keep the higher red list category in the database) and any taxa not given in Latin. Handling nomenclature autonyms, i.e. taxa for which the species epithet is repeated in infraspecific epithet (e.g., *Odontarrhena nebrodensis* subsp. *nebrodensis*, *Lobelia spicata* var. *spicata*) was complex as some red lists included both the species and autonym while others included the autonym. According to the International Code of Botanical Nomenclature (Accessed October 2022 to March 2023, https://www.bgbm.org/iapt/nomenclature/code/SaintLouis/0001ICSLContents.htm) autonyms at this level are

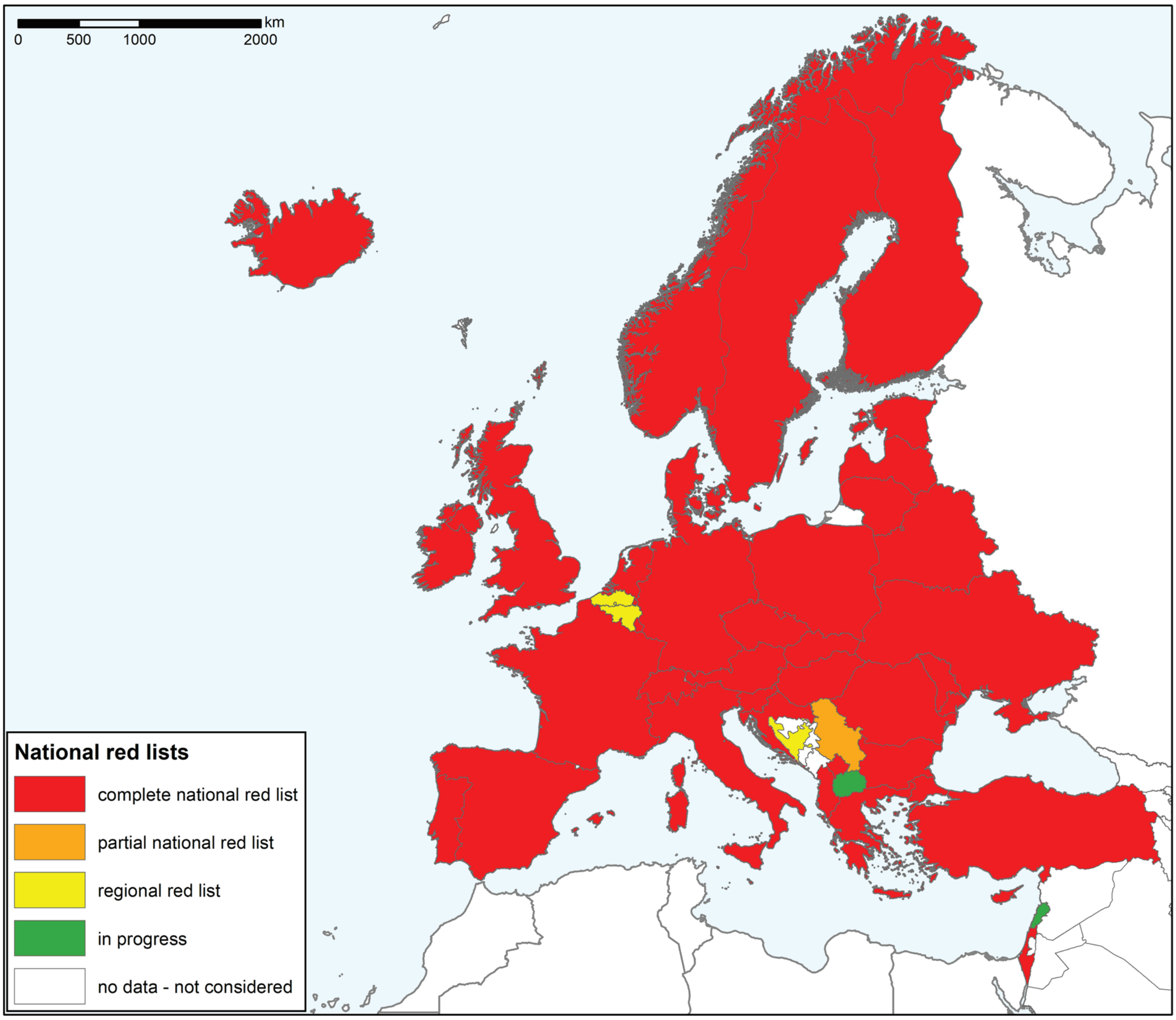

Fig. 2 National red lists of the European vascular flora included in the database. For countries in red colour, the national red list was available and included in the database. For Serbia (orange), only the national red list for taxa classified as regionally extinct or critically endangered is available. We compiled regional red lists for the Federation of Bosnia and Herzegovina and Flanders and Vallonia (yellow). In North Macedonia and Lebanon, the national red lists were in progress (green). For North Macedonia, we did not include any data in the database as only a few taxa were assessed; in the case of Lebanon, we included the available taxa in the assessment.

automatically established at the first instance of valid publication of a name of an infraspecific taxon that includes the type of the adopted, under a legitimate species name. As a result, autonyms are not followed by an author citation. It was out of scope for this study to check whether the subordinate taxa which established the autonym had been validly published.

The second column of each country's spreadsheet captured the red list category, taken directly from the sources, with a few exceptions where we revised them. For example, if countries used the categories Extinct (EX) or Extinct in the Wild (EW) to describe taxa that were nationally EX or EW, we assigned them with the appropriate national categories, RE or REW, after checking the taxa distribution in EuroMed database (Accessed October 2022 to March 2023, https://europlusmed.org/). In a few cases, countries assigned two distinct IUCN categories to a taxon (e.g., Czech Republic, *Scilla bifolia* subsp. *spetana*, CR/EN), implying there is not enough data available to determine which one. In such cases, we retained the highest category; for this example, CR (Supplementary Table S2).

There were 19 national red lists where taxonomic names were listed without scientific authorships. To include those lists into the database and enable use for analyses across countries, we had to assign the correct scientific authorships to their taxa and harmonize the taxonomic names across all red lists. To ensure a uniform approach to handling taxonomic names across all red lists, we opted to exclude scientific authorships from the remaining red lists that originally included them. We then assigned correct scientific authorships to taxa in all red lists using a reliable Taxonomic Name Backbone (TNB). This process is described in more detail under the section "Identifying the taxonomic name backbone".

Column name	Description
Database ID	Unique database identification number assigned to each record
Country	Name of country or biogeographic unit (e.g., Island of Ireland) to which the red list belongs to
Sub-country	Region within country (relevant only for Belgium)
Kingdom	The plant kingdom as Plantae
Family-original taxonomic name	Family of the original taxonomic name (i.e., taxonomic name extracted from countries' red list)
Original taxonomic name	Taxonomic name extracted from countries' red lists
Name backbone used	Taxonomic name backbone (TNB) used to determine the most up-to-date taxonomic status - and to establish accepted taxonomic name with scientific authorships (POWO – The Plants of the World Online; WFO – World Flora Online)
Life Sciences Identifier (LSID)-accepted taxonomic name	Unique identifiers assigned by International Plant Names Index (IPNI) to identify each taxonomic name. In the absence of LSID, unique identifier of the record.
Family-accepted taxonomic name	Family of the accepted taxonomic name assigned by authors using summarised TNBs and confidence levels
Accepted taxonomic name without authorships	Accepted taxonomic name without scientific authorships assigned by authors using summarised TNBs and confidence levels
Authorships-accepted taxonomic name	Scientific authorship for accepted taxonomic name assigned by authors using summarised TNBs and confidence levels
Accepted taxonomic name with authorship	Concatenation of accepted taxonomic name with scientific authorships above
Confidence level	Level of precision for assigning an accepted taxonomic name with scientific authorship
Confidence level description	Detailed description of confidence level determination
Red list category	Red list category listed in original red lists
Standardized red list categories	Red list category harmonized to reflect the currently valid IUCN regional red listing categories (IUCN 2012). The harmonisation process is described in Supplementary Table S2.
References	The original source from where the data were extracted (e.g., book, article, report, website, etc.). Where applicable, references were translated to English. References are available in the original and English language in Supplementary Table S1.

Table 1. Summary of database columns.

Data consolidation and cleaning. The subsequent processes of data handling, cleaning, formatting, and checking for accuracy of taxonomic names were performed using Microsoft® Access® for Microsoft 365 Microsoft Office software[72]. A total of 42 datasets from 41 countries were merged into one file with four columns to capture the name of the country, where applicable also the region of the country to which the red list belongs, original taxonomic name, and red list category. Each record was then assigned with a unique database Identification number (ID). The data cleaning process for taxonomic names was extended to correct or remove obvious mistakes in spelling, capitalization, abbreviations, hybrid sign, non-Latin attributes, diacritics, hyphenated epithets or vice-a-versa, and misapplied gender (e.g., epithet does not agree with the gender of genus). This step resulted in transforming the dataset to a consistent format enabling the subsequent data matching process through checking the accuracy of taxonomic names with widely used nomenclature and/or taxonomic databases. The data cleaning process was repeated whenever we found an error on extracted original data, until the final database was established.

Red list categories harmonization. Due to the high variability in red list categories, harmonizing them to the current IUCN categories while maintaining their integrity, i.e. not changing the intended conservation status, was essential. We followed the most recent IUCN national red listing guidelines[10]. We also consulted previous IUCN publications on red listing[6–8,24–26,73], unique red listing categorizations adopted by individual countries, and COST Action country representatives to propose harmonization of certain categories (e.g., for Latvia, Germany and Malta which had their own categorization; for other countries that used the old IUCN category R – rare, etc.). The output of category harmonization is available in Supplementary Table S2[6,8,23,24,26,31–33,35–39,41,43,46,48,51–54,56,59–61,66,69,74,75].

Identifying the taxonomic name backbone. Various nomenclatures were applied by countries to record taxonomic names in red lists, as they relied on a wide range of references, current or outdated. This resulted in countries' red lists having not only different taxonomic names, but also sometimes different scientific authorships for essentially the same taxon, and some countries lacking scientific authorship all together. To resolve this, harmonizing the taxonomic name usage among datasets to ascertain their accuracy was essential. To accomplish the harmonisation of taxonomy, we needed a plant taxonomic name backbone (TNB), i.e. a database containing the most up-to-date and comprehensive list of world's vascular plants flora with taxonomic names with their scientific authorships and taxonomic status (e.g., Accepted, Synonym, Unplaced, etc.). We identified two TNBs which are regularly curated, widely used, and available online. The Plants of the World Online (POWO, Accessed October 2022 to March 2023, https://powo.science.kew.org/) was chosen as the primary TNB and the World Flora Online (WFO, Accessed October 2022 to March 2023, https://www.worldfloraonline.org/) as the secondary TNB. These databases document the world's flora by family, taxonomic name, scientific authorities, taxonomic status along with references. We used these databases to verify the accuracy of taxonomic names in the dataset and to establish accepted taxonomic names with scientific authorships and families. The TNBs used evolve at a fast pace and therefore, the taxonomic names used for the matching of the red lists reflect only a certain point in time (day, month, and year when we accessed the data). This implies some taxa statuses may have changed since then, i.e. may have been allocated a different scientific authorship, and/or taxonomic status.

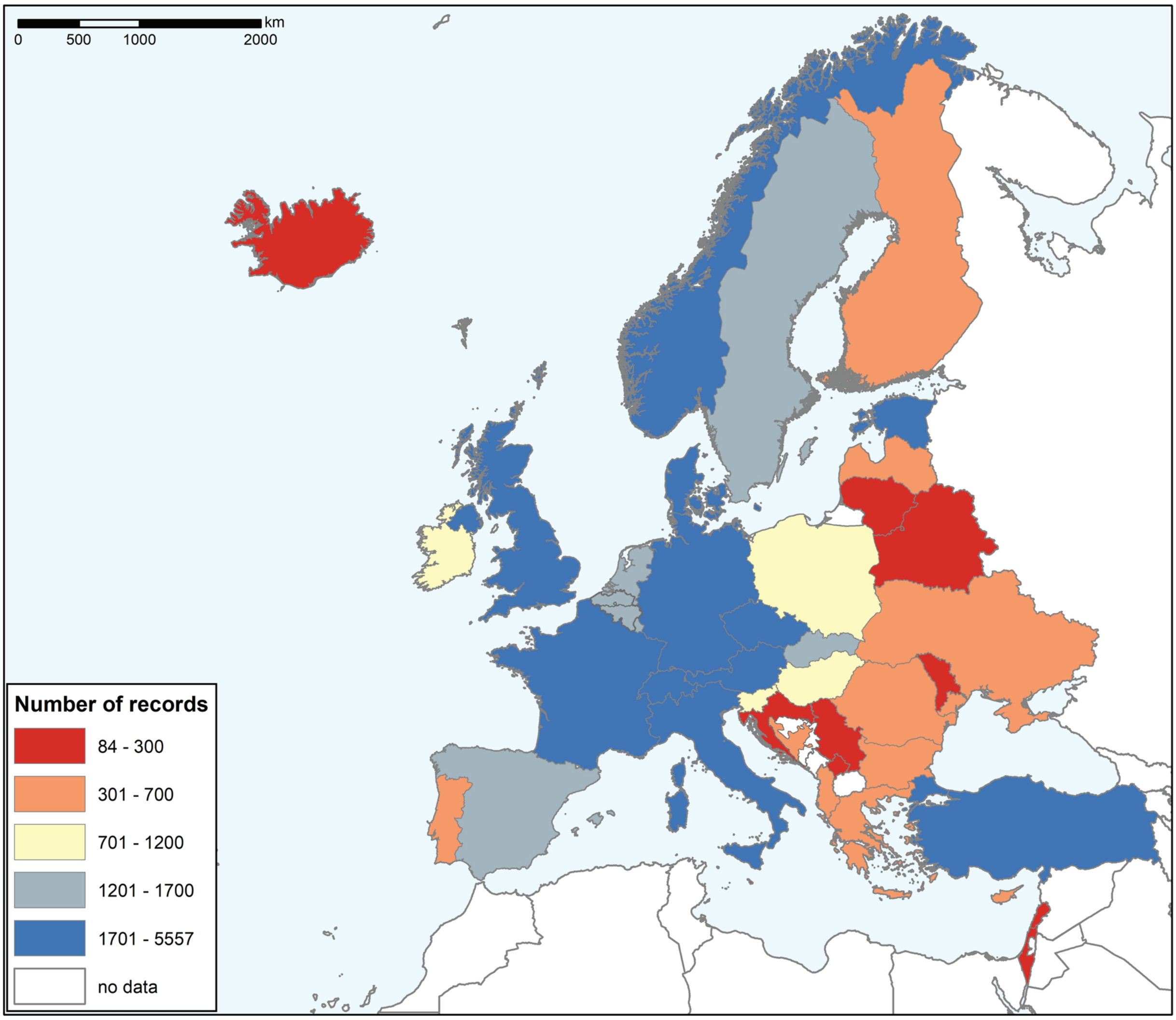

Fig. 3 Number of records per country.

In rare cases, in the absence of a taxonomic name in both POWO and WFO, or when there was conflicting evidence between the two, we also used the International Plant Names Index (IPNI, Accessed October 2022 to March 2023 https://www.ipni.org/), as an authoritative source of objective nomenclature data which collects, combines and indexes nomenclatural acts (including spelling, author(s), type(s), place and date of publication)[76].

Establishing confidence levels. Matching the taxonomic name alone to accepted taxonomic names with scientific authorships in TNBs was not sufficient to complete the database. For instance, there are situations where a particular taxonomic name has multiple records in TNBs and each with different scientific authorships linked to different accepted taxonomic names, representing dissimilar taxon identities (e.g., *Salsola oppositifolia* Desf. - synonym of *Soda oppositifolia* (Desf.) Akhani; *Salsola oppositifolia* Pall. - synonym of *Petrosimonia sibirica* (Pall.) Bunge; and *Salsola oppositifolia* Sieber ex Moq. - synonym of *Soda longifolia* (Forssk.) Akhani). Therefore, we established an approach with confidence levels, denoting the precision level of assigning an accepted taxonomic name to a taxonomic name from the red lists in the absence of its scientific authorship. First, each individual taxonomic name listed on TNBs, from species to infraspecific epithet level, was extracted in a table with various summary counts. Each summary count included the total numbers of records, the number of records that are identified as accepted, synonym, artificial hybrids, local biotype, unplaced/unchecked, illegitimate, invalid, misapplied, or orthographic, the number of different accepted names and the number of records linked to the same accepted name.

The next step was to allocate the confidence levels to each taxon in summarised table. Three confidence levels (HIGH, MEDIUM, NONE with precision levels from 100%, $\geq$75-$<$100% to 0%, respectively) were established depending on the nature of summary counts, and how easy or complex to assign accepted taxonomic names with scientific authorships. Whilst setting confidence levels for some taxonomic names was straight forward (e.g., HIGH: one accepted name; NONE: one name not linked to an accepted name) others were more complex and required reviewing the summary counts (e.g., HIGH: two or multiple names but all shared the same accepted name; MEDIUM: two names, one accepted and the other is a synonym which is linked to a different accepted

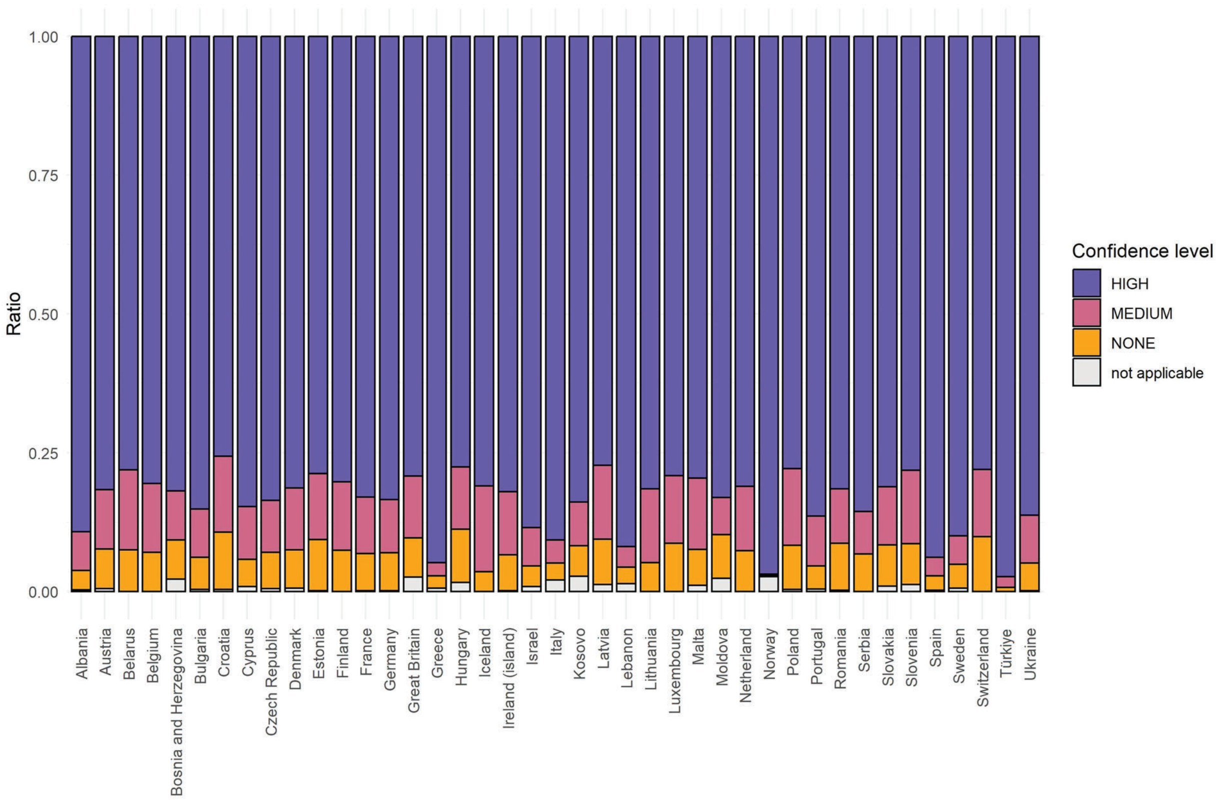

Fig. 4 Distribution of confidence levels across countries.

name; MEDIUM: two names, one accepted and the other is not linked to an accepted name; NONE: multiple names linked to different or without accepted names). Taxonomic names estimated with HIGH and MEDIUM confidence levels were allocated with accepted taxonomic names with their scientific authorships and family. Those with confidence levels of NONE were left blank. The category 'not applicable' was assigned to unmatched taxonomic names. For accepted taxonomic names we also extracted the Life Sciences Identifier (LSID) assigned by International Plant Names Index. In the absence of LSID, we extracted the unique identifier of the record.

The following examples illustrate various scenarios of reviewing summary counts and how confidence levels were set when summarising POWO (2022) records. To capture all these scenarios, we used a methodical and step by step approach by setting up a series of queries in Microsoft® Access® software[72].

1. HIGH – 100% precision:

    a. Only one record in TNB and it is an accepted taxonomic name.
    e.g., *Syzygium cartilagineum* Merr. & L.M.Perry is an accepted name.
    b. Only one record in TNB which is not accepted but linked to an accepted name.
    e.g., *Litsea macrocarpa* Blume is a synonym of *Nothaphoebe macrocarpa* (Blume) Meisn. which is an accepted name.
    c. Multiple records in TNB but all are linked to the same accepted name.
    e.g., *Polygonum natans* Hegetschw., *Polygonum natans* Gueldenst., and *Polygonum natans* Eaton are synonyms of *Persicaria amphibia* (L.) Delarbre which is an accepted name.
    d. Multiple records in TNB, one is an accepted name, and others are linked to the accepted name.
    e.g., *Crotalaria alata* Buch.-Ham. ex D.Don is an accepted name. *Crotalaria alata* H.Lév. and *Crotalaria alata* Roxb. are synonyms of *Crotalaria alata* Buch.-Ham. ex D.Don.
    e. Local or singular biotype.
    e.g., *Hieracium diodontum* (Stenstr.) Omang
    f. Artificial hybrids.
    e.g., *Viola* × *wittrockiana* Gams
    g. When taxonomic names are validated against references or confirmed by in-country experts.

2. MEDIUM – ≥75-<100% precision:

    a. Two records in TNB, one is an accepted name, and the other is linked to a different accepted name, but we assumed that the name is referring to the accepted name.
    e.g., *Carex furva* Webb is an accepted name but *Carex furva* (L.H.Bailey) Piper is a synonym of *Carex praticola* Rydb.

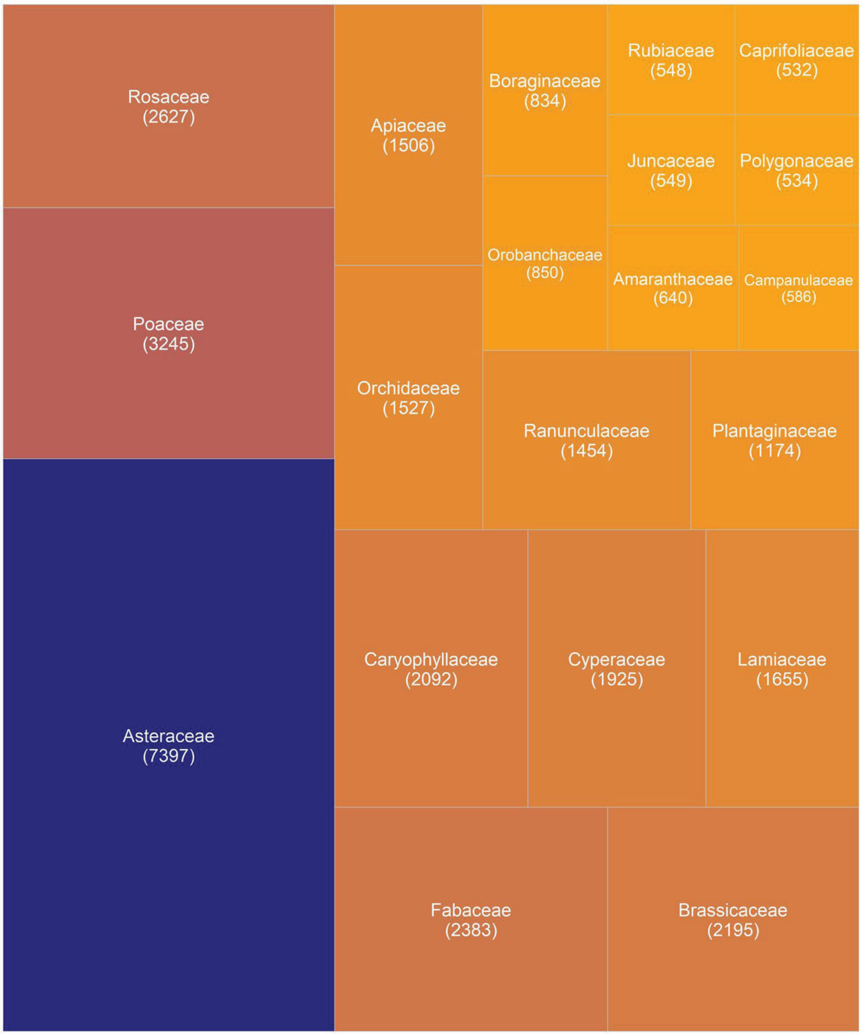

Fig. 5 Number of records per family. Only 20 families with highest number of records are visualized.

   b. Two records in TNB, one is an accepted name, and the other is not linked to an accepted name, but we assumed that the name is referring to the accepted name.
   e.g., *Dianthus floribundus* Boiss. is an accepted name but *Dianthus floribundus* Sennen is an unplaced name.

3. NONE – 0 precision:

   a. One record in TNB but without an accepted name.
   e.g., *Rhaponticum scariosum* Lam. is an unplaced name.
   b. Multiple records in TNB, some are unplaced, some linked to different accepted names, or some are not linked to accepted names, etc.
   e.g., 13 records - *Rosa collina* Raf., *Rosa collina* Godet, *Rosa collina* Schrank, *Rosa collina* Boreau, *Rosa collina* Déségl., *Rosa collina* DC., *Rosa collina* Cariot, *Rosa collina* J.B.Keller, *Rosa collina* M.Bieb., *Rosa collina* Dumort., and *Rosa collina* Sabr. are unplaced names, *Rosa collina* Sm. is synonym of *Rosa stylosa* Desv. and *Rosa* × *collina* Jacq. is synonym of *Rosa* × *alba* L.

Matching taxonomic names and data cleaning. The summarised table for each TNB included data columns to capture unique list of taxonomic names (without scientific authorships) and their family, assigned confidence levels and their descriptions, accepted taxonomic names and their family and LSID (or unique identifiers of the record), and corresponding summary counts. Data column containing the unique list of taxonomic names was matched against those in red lists, first using summarised table of POWO and then any unmatched names with WFO. Whilst a wide range of online tools are available for checking the accuracy of taxonomic names, we used an alternative and methodical approach using a set of Microsoft® Access®[72] SQL queries. This approach enabled to review results at each step and made decisions either to progress to next step, improve the algorithms used for matching or go through a cycle of data cleaning.

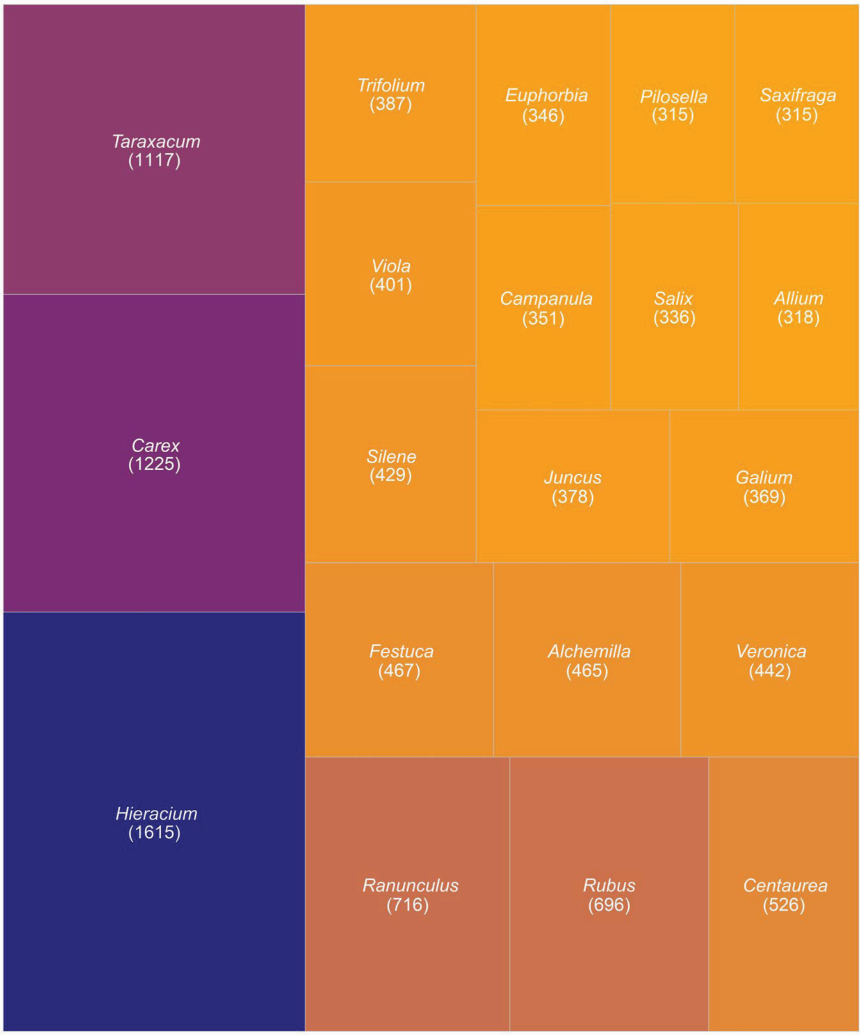

Fig. 6 Number of records per genera. Only 20 genera with highest number of records are visualized.

When there was an exact match, associated confidence levels and taxonomic data (e.g. families, accepted taxonomic names and their scientific authorships and LSID) were extracted from TNBs and combined with red list data. When exact matching was failed, the fuzzy matching was done up to two-character difference at the beginning or end of the string to check the alignment. These were done in increment by adding genus, species epithet, infraspecific rank and intraspecific epithet, to track at which stage the mismatch was introduced. Fuzzy matches were checked on a record-by-record basis, inaccuracies were resolved manually and the matching process was then repeated.

Unmatched names went through cycles of data cleaning to maximize the taxonomic name matching process with TNBs. To investigate likely causes for mismatches, additional resources were used to find and correct inaccuracies of taxonomic names e.g., the IPNI, Euro + Med Plantbase, Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) and Tropicos (https://www.tropicos.org/home).

We have endeavoured to make the database as comprehensive as possible to facilitate future improvements [10.6084][19]. We have retained taxonomic names falling to either matched but with a confidence level of 'NONE' or unmatched (not found a match with TNB) without excluding them. Confidence levels were not applicable for unmatched taxonomic names.

Data Records

The static version of the dataset is freely available via figshare repository [10.6084][19], with this section being the primary source of information on the availability and content of the data being described (Table 1). Technical validation of the database is also freely available via figshare repository [10.6084][20], with section 'Technical validation' being its primary source of information.

Our database is a comprehensive overview of red listed vascular plant taxa from almost all European countries (39 out of 44) and two countries outside of Europe but in the Mediterranean. Data for each country is presented in rows with a unique database ID and amounts to 51,109 records containing 21,481 revised original taxonomic names (Fig. 3). There was a notable difference between the number of records and taxa, as same taxon appeared on multiple red lists due to its distribution range across countries. Data records per country ranged from 84 (Iceland) to 5537 (France). Using confidence levels, we assigned accepted taxonomic names with scientific authorships and families to 20,312 of the original taxonomic names across 47,701 records: 43,204 with HIGH and 4497 with MEDIUM precision. However, 3411 records with >1000 original taxonomic names were not assigned with accepted taxonomic names: 3033 with NONE precision; and 378 records where precision was 'not applicable' as taxonomic names of red lists were not matched with TNBs. Overall, there are 17,873 unique accepted taxonomic names from 184 families, 1650 genera and 15,593 species. Across countries, the distribution of confidence levels highlighted a similar pattern; the majority of records from red lists were assigned with HIGH confidence level, followed by MEDIUM (Fig. 4). When exploring the records attached with accepted taxonomic names, 12 families represented 61% of the list (Fig. 5; number of records and taxa in brackets, respectively): Asteraceae (7397, 4194); Poaceae (3245, 876); Rosaceae (2627, 1160); Fabaceae (2383, 923); Brassicaceae (2195, 896); Caryophyllaceae (2092, 887); Cyperaceae (1925, 329); Lamiaceae (1655, 751); Orchidaceae (1527, 247); Apiaceae (1506, 511); Ranunculaceae (1454, 527); and Plantaginaceae (1174, 344). The six most recorded genera are (Fig. 6; number of records and taxa in brackets, respectively): *Hieracium* (1615, 1355); *Carex* (1225, 227); *Taraxacum* (1117, 706*); Ranunculus* (716, 271*); Rubus* (696, 460); *Centaurea* (526, 379).

Technical Validation

To prove the accuracy of assigning MEDIUM and HIGH confidence levels, we extracted, respectively, eight and two records of said confidence levels for each country. The records were extracted manually and as randomly as possible. We verified their taxonomic identities following two methods: (i) by sending the records to respective COST Action country representatives, so that experts could check the accuracy by referring to original references such as taxon publication or an established country flora, (ii) by checking ourselves against red lists or countries checklists of vascular plants, where scientific authorships are listed. The table sent to experts contained columns already completed by us (name of country, revised original taxonomic name from the national red list, accepted taxonomic name with scientific authorships assigned by us, and confidence level), and columns to be completed by the recipient if there is a disagreement (technical validation i.e., scientific authorship to original taxonomic name, reference and URL if available). The validation process was done for 40 countries and 41 red lists. One country was excluded from the validation process, Moldova, as we have not received a response or not found a suitable resource to conduct validation against (e.g., plant checklist, as the country red list did not contain scientific authorships).

In total, we performed technical validation for 317 MEDIUM and 91 HIGH confidence level records[20]. The technical validation dataset is available via figshare repository [10.6084][20].Discrepancies between the scientific authorships assigned by us appeared for a total of 36 records, i.e. 8.82% of the validated records. Out of those, 18 were of HIGH confidence level and 18 were of MEDIUM confidence level. Thirty-one had minor disputes, often where the red list or national flora used as a reference was an older document and there was a discrepancy with TNBs (historic versus current alternative taxonomies). For all these cases we selected scientific authorships provided on TNBs, containing the most up-to-date references. We had five slightly more complex disputes, 1.22% of the whole sample. The technical validation confirmed 99.26% of success (91.18% in agreement with methodology without a dispute +8.08% the evidence supported methodology over dispute) in our approach.

Usage Notes

The database is presented in an end-user friendly spreadsheet format and open to revision by interested parties. The dataset is available for download as a flat csv file from the figshare repository [10.6084][19] and have no restriction on re-use. Using columns 'Accepted taxonomic name with authorship' and 'Country' or 'Sub-country', data can be joined to other external data sets. As the TNBs used for this study evolve on a day-to-day basis and the database is static, the users must take extra care when addressing nomenclature disputes on integrity of accepted taxonomic names and their scientific authorships. We welcome reporting possible errors to the corresponding author.

We anticipate several uses of this database, primarily as a useful 'One Stop Resource' for red listed plants, in particular for the most threatened (CR, EN and VU) in Europe and the Mediterranean. The database provides data for comparative analysis at taxon or family level to explore trends across Europe, individual or groups of countries or habitat types.

Code availability

No custom code has been used to produce this database.

Received: 28 March 2024; Accepted: 3 October 2024;
Published online: 16 October 2024

References

1. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B. & Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **403**, 853–858 (2000).
2. Bilz, M., Kell, S. P., Maxted, N. & Lansdown, R. V. *European Red List of Vascular Plants.* https://data.europa.eu/doi/10.2779/8515 (2011).
3. Antonelli, A. *et al. State of the World's Plants and Fungi, 2023.* https://doi.org/10.34885/wnwn-6s63 (2023).
4. Rodrigues, A. S. L., Pilgrim, J. D., Lamoreux, J. F., Hoffmann, M. & Brooks, T. M. The value of the IUCN Red List for conservation. *Trends Ecol. Evol.* **21**, 71–76 (2006).
5. Butchart, S. H. M. *et al.* Measuring Global Trends in the Status of Biodiversity: Red List Indices for Birds. *PLOS Biol.* **2**, e383 (2004).
6. IUCN. *Guidelines for Using the IUCN Red List Categories and Criteria. Version 15.1.* https://www.iucnredlist.org/resources/redlistguidelines (2022).
7. IUCN. *The IUCN Red List Categories and Criteria: Comparison between Versions 2.3 (1994) and 3.1* https://nc.iucnredlist.org/redlist/resources/files/1530881462-rl_criteria_1994_versus_2001.pdf (2001).

8. IUCN. *Guidelines for Application of IUCN Red List Criteria at Regional and National Levels: Version 4.0*. https://portals.iucn.org/library/node/10336 (2012).
9. Maes, D. *et al*. The use of opportunistic data for IUCN Red List assessments. *Biol. J. Linn. Soc.* **115**, 690–706 (2015).
10. Glasnović, P. *et al*. Assessing the national red lists of European vascular plants: Disparities and implications. *Biol. Conserv.* **293**, 110568 (2024).
11. Mikkelson, G. M., Gonzalez, A. & Peterson, G. D. Economic Inequality Predicts Biodiversity Loss. *PLOS ONE* **2**, e444 (2007).
12. Griffiths, H. I., Kryštufek, B. & Reed, J. M. *Balkan Biodiversity Pattern and Process in the European Hotspot*. (Springer, 2004).
13. *State of Nature Conservation Systems in South-Eastern Europe*. https://doi.org/10.2305/IUCN.CH.2018.19.en (IUCN, 2018).
14. Balmford, A., Gaston, K. J., Blyth, S., James, A. & Kapos, V. Global variation in terrestrial conservation costs, conservation benefits, and unmet conservation needs. *Proc. Natl. Acad. Sci.* **100**, 1046–1050 (2003).
15. Baakman K. Testing times: The effectiveness of five international biodiversity-related conventions. (Tilburg University, Wolf Legal Publishers (WLP), 2011).
16. Hermoso, V., Morán-Ordóñez, A., Canessa, S. & Brotons, L. Four ideas to boost EU conservation policy as 2020 nears. *Environ. Res. Lett.* **14**, 101001 (2019).
17. OECD. *OECD Environmental Performance Reviews: Greece 2020*. https://www.oecd-ilibrary.org/environment/oecd-environmental-performance-reviews-greece-2020_cec20289-en (2020).
18. Holz, H., Segar, J., Valdez, J. & Staude, I. R. Assessing extinction risk across the geographic ranges of plant species in Europe. *PLANTS PEOPLE PLANET* **4**, 303–311 (2022).
19. Liu, U., Lončarević, N. & Glasnović, P. Database of European vascular plants red lists. *figshare* https://doi.org/10.6084/m9.figshare.26982994 (2024).
20. Lončarević, N., Liu, U. & Glasnović, P. Technical validation of the Database of European vascular plants red lists. *figshare* https://doi.org/10.6084/m9.figshare.26982994 (2024).
21. Wasowicz, P. & Heiðmarsson, S. A vascular plant red list for Iceland. *Bot. Isl.* 31–48, https://doi.org/10.5281/zenodo.2875162 (2019).
22. *Atlas and Red Book of the Threatened Vascular Flora of Spain. Addendum 2017*. (Ministry for the Ecological Transition-Spanish Society of Plant Conservation Biology, Madrid, Spain, 2019).
23. Sparrius, L., Odé, B. & Beringen, R. *Base Report Red List Vascular Plants 2012 According to Dutch and IUCN Criteria*. https://doi.org/10.13140/RG.2.2.19320.96006 (2014).
24. Dihoru, G. & Negrean, G. *Red Book of Vascular Plants in Romania*. (Romanian Academy and Bucharest Institute of Biology, Bucharest, 2009).
25. *Cartea roșie a Republicii Moldova: The red book of the Republic of Moldova*. (Știința, Chișinău, Republica Moldova, 2015).
26. *Red Book of Vascular Flora of Croatia: Categories EX, RE, CR, EN and VU*. (Ministry of Culture of the Republic Croatia, State Institute for Nature Protection, Zagreb, Croatia, 2005).
27. Dagher Kharrat, M. B. & Elzein, H. *Determination of Important Areas for Plants and Creation of Micro-Reserves to Conserve Rare or Endemic Species in Lebanon*. https://www.cepf.net/sites/default/files/final-project-report-63257.pdf (2017).
28. *Endangered Species in Finland - Red Book*. (Ministry of the Environment & Finnish Environment Agency, Helsinki, Finland, 2019).
29. El Zein, H. & Kahale, R. First comprehensive IUCN Red List assessment of 100 endemic species of the flora of Lebanon. *Flora Mediterr*. **32** (2022).
30. Saintenoy-Simon, P. J. *et al*. *First List of Rare, Threatened and Protected Species in the Wallonian Region (Pteridophytes and Spermatophytes)*. https://biodiversite.wallonie.be/servlet/Repository/liste-especes-vegetales-protegees-wallonie-201202.pdf?ID=21768&saveFile=true (2006).
31. Orsenigo, S. *et al*. Global and Regional IUCN Red List Assessments: 9. *Ital. Bot.* **9**, 111–123 (2020).
32. Fenu, G. *et al*. Global and Regional IUCN Red List Assessments: 10. *Ital. Bot*. **10** (2020).
33. Orsenigo, S. *et al*. Global and Regional IUCN Red List Assessments: 11. *Ital. Bot.* **11**, 131–143 (2021).
34. Wyse Jackson, M. *et al*. *Ireland Red List No. 10: Vascular Plants*. https://www.npws.ie/sites/default/files/publications/pdf/RL10%20VascularPlants.pdf (2016).
35. Rossi, G. *et al*. Is legal protection sufficient to ensure plant conservation? The Italian Red List of policy species as a case study. *Oryx* **50**, 431–436 (2016).
36. Andrušaitis, G. & Vimba, É. K. *Red Data Book of Latvia: Rare and Endangered Species of Plants and Animals*. (Institute of biology - Latvian Academy of Sciences: European Commission - Directorate General XI, Riga, 2003).
37. Millaku, F. *et al*. *The Red Book of Vascular Flora of the Republic of Kosovo*. https://www.ammk-rks.net/assets/cms/uploads/files/Publikime-raporte/The_Red_Book_of_Vascular_Flora_of_Republic_of_Kosovo-_English_(Summary).pdf (2013).
38. NGO Nezahat Gökyiğit Botanical Garden & NGO Ali Nihat Gökyiğit. List of threatened plant species. http://www.tehditaltindabitkiler.org.tr/ (2022).
39. Carapeto, A., Francisco, A., Pereira, P. & Porto, M. *Red List of the Vascular Flora of Mainland Portugal*. https://www.repository.utl.pt/handle/10400.5/21792 (2020).
40. Israel Nature and Parks Authority. Nature risk assessment portal in Israel, Endangered plants. https://redlist.parks.org.il/plants/list/ (2021).
41. French Committee of the International Union for the Conservation of Nature (IUCN France), Federation and network of National Botanical Conservatories (FCBN), French Agency for Biodiversity (AFB) & National Museum of Natural History (MNHN). *Red List of Threatened Species in France - Vascular Flora of Metropolitan France*. https://inpn.mnhn.fr/docs/LR_FCE/Liste_rouge_Flore_vasculaire_Metropole_2018.pdf (2018).
42. Norwegian red list for species. The Species Data Bank https://www.artsdatabanken.no/lister/rodlisteforarter/2021 (2021).
43. Andrienko, T. L. & Peregrym, M. M. Official lists of regional rare plants of administrative territories of Ukraine. https://www.botany.kiev.ua/doc/of_reg_sp.pdf (2012).
44. Ministry of tourism and environment. *Order 1280/2013: Approval of the red list of wild flora and fauna*. https://faolex.fao.org/docs/pdf/alb144233.pdf (2013).
45. Domashlinets, V. Order No. 11 On approval of lists of plant and mushroom species included in the Red Book of Ukraine (plant life) and plant and mushroom species excluded from the Red Book of Ukraine (plant life). https://zakon.rada.gov.ua/laws/show/z0370-21#Text (2021).
46. Kaźmierczakowa, R. *et al*. *Polish Red List of Pteridophytes and Flowering Plants*. https://www.researchgate.net/publication/313475016_Polish_red_list_of_pteridophytes_and_flowering_plants (2016).
47. *Red Book of the Republic of Belarus. Plants. Rare and Endangered Species of Wild Plants*. (Ministry of Natural Resources and Environmental Protection, Minsk, Belarus, 2006).
48. *Red Data Book for the Maltese Islands*. (Ministry of education, Department of information, 1989).
49. *Red Data Book of Lithuania*. (Ministry of the Environment, 2007).
50. Bulgarian Academy of Sciences & Ministry of Environment and Water. Red data Book of the Republic of Bulgaria, Plants and fungi. http://e-ecodb.bas.bg/rdb/en/vol1 (2011).
51. Red List and Total Species List of Ferns and Flowering Plants (Trachaeophyta) in Germany. in *Red List of endangered animals, plants and fungi in Germany* (eds. *et al*.) (Naturschutz und Biologische Vielfalt 70(7): 13–358, 2018).
52. *Red list of ferns and flowering plants in Austria*. https://www.zobodat.at/pdf/STAPFIA_0114_0001-0357.pdf (2022).

53. Eliáš, P., Dítě, D., Kliment, J., Hrivnák, R. & Feráková, V. Red list of ferns and flowering plants of Slovakia, 5th edition. *Biologia (Bratisl.)* **70**, 218–228 (2015).
54. Anonymous. *Red List of Ferns and Seed Plants (Pteridophyta & Spermatophyta)*. https://www.uradni-list.si/files/RS_-2002-082-04055-OB~P001-0000.PDF (2001).
55. Đug, S., Muratović, E., Drešković, N., Boškailo, A. & Dudević, S. *Red List of Flora of Bosnia and Herzegovina*. https://www.fmoit.gov.ba/upload/file/okolis/Crvena%20lista%20Faune%20FBiH.pdf (2013).
56. *Red List of the Vascular Flora of Hungary*. https://www.researchgate.net/publication/256839045_Red_list_of_the_vascular_flora_of_Hungary_Voros_Lista_A_magyarorszagi_edenyes_flora_veszelyeztetett_fajai (2007).
57. Colling, G. Red List of the vascular plants of Luxembourg. *Ferrantia* **42**, 1–77 (2005).
58. *Red List of Threatened Species of Czech Republic: VASCULAR PLANTS*. https://www.researchgate.net/publication/313475016_Polish_red_list_of_pteridophytes_and_flowering_plants (2017).
59. Orsenigo, S. *et al*. Red list of threatened vascular plants in Italy. *Plant Biosyst. - Int. J. Deal. Asp. Plant Biol.* **155**, 310–335 (2021).
60. Bornand, C. *et al*. *Red List Vascular Plants. Endangered Species in Switzerland*. https://www.infoflora.ch/en/assets/content/documents/roteliste_pflanzen_d_20160908.pdf (2016).
61. Orsenigo, S. *et al*. Red Listing plants under full national responsibility: Extinction risk and threats in the vascular flora endemic to Italy. *Biol. Conserv.* **224**, 213–222 (2018).
62. Kull, T. *et al*. *Summary of Vascular Plant Vulnerability Assessment Results 2017-2018, Species Threat Assessment of Public Procurement 183098 Part No. 15 - Flowering Plants (Anthophyta), Conifers (Coniferophyta), Leafy Plants (Monilophyta) and True Rhizomes (Lycopodiophyta)*. https://www.etis.ee/Portal/Publications/Display/db30aec6-b4f1-4eb4-8916-b985b4e6905a (2018).
63. Moeslund, J. E. *et al*. The Danish red list. Aarhus Universitet, DCE–National Center for Environment and Energy https://doi.org/www.redlist.au.dk (2019).
64. *The Red Data Book of Rare and Threatened Plants of Greece*. (WWF, Athens, Greece, 1995).
65. *The Red Data Book of Rare and Threatened Plants of Greece, Volume 1 (A-D) & Volume 2 (E-Z)*. (Hellenic Botanical Society, Patras, Greece, 2009).
66. *The Red Data Book of the Flora of Cyprus*. (Cyprus Forestry Association, Lefkosia, Cyprus, 2007).
67. Stevanović, V. *The Red Data Book of the Flora of Serbia. Extinct and Critically Endangered Taxa*. (Ministry of Environment of the Republic of Serbia, 1999).
68. SLU Artdatabanken. The Swedish Red List. https://doi.org/10.15468/jhwkpq via GBIF.org (2020).
69. Cheffings, C. M. & Farrell, L. (Eds.). *The Vascular Plant Red Data List for Great Britain*. 1–116, https://data.jncc.gov.uk/data/cc1e96f8-b105-4dd0-bd87-4a4f60449907/SpeciesStatus-7-VascularPlant-WEB-2005.pdf 1–116 (2005).
70. Maes, D. *et al*. Validated red lists of Flanders, Belgium. Research Institute for Nature and Forest (INBO) https://doi.org/10.15468/8tk3tk accessed via GBIF.org (2020).
71. Microsoft Corporation, Inc. Microsoft Excel. Microsoft Corporation, Inc.
72. Microsoft Corporation, Inc. Microsoft Access. Microsoft Corporation, Inc.
73. Davis, S. D. *et al*. *Plants in Danger: What Do We Know?* (IUCN, Gland, Switzerland and Cambridge, U.K., 1986).
74. IUCN Species Survival Commission (SSC). *IUCN Red List Categories*. https://portals.iucn.org/library/efiles/documents/1995-008.pdf (1994).
75. IUCN. *List of Rare, Threatened and Endemic Plants in Europe (1982 Edition)*. https://portals.iucn.org/library/node/5851 (1983).
76. Gärdenfors, U., Hilton-Taylor, C., Mace, G. M. & Rodríguez, J. P. The Application of IUCN Red List Criteria at Regional Levels. *Conserv. Biol.* **15**, 1206–1212 (2001).

Acknowledgements
This article is based upon work from COST Action CA18201, supported by COST (European Cooperation in Science and Technology). The authors express gratitude to the COST Action CA18201 for granted space and opportunity for authors to collaborate. The research was supported by the Slovenian research and innovation agency/Javna agencija za znanstvenoraziskovalno in inovacijsko dejavnost Republike Slovenije (ARIS) - infrastructural program I0-0035/infrastrukturni program I0-0035.

Author contributions
Nina Lončarević compiled and cleaned red lists data, harmonized red list categories, prepared individual datasets for merging into the database and wrote the manuscript. Udayangani Liu completed data cleaning, harmonized taxonomic names, developed the database and wrote the manuscript. Peter Glasnović conceived the research idea, mentored the first author, produced maps and figures and edited the manuscript. The other co-authors were COST Action representatives who were involved in providing red lists, cleaning data, conducting the technical validation, contributed to conceiving the database development and/or reviewing the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41597-024-03963-0.

Correspondence and requests for materials should be addressed to P.G.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Nina Lončarević[1,37], Udayangani Liu[2,37], Anastasia Stefanaki[3,4], André Carapeto[5], Andreas Ensslin[6], Conor Meade[7], Detlev Metzing[8], Dhimiter Peci[9], Edy Fantinato[10], Guy Colling[11], Hana Pankova[12], Ieva Akmane[13], Ivaylo N. Tsvetkov[14], Jozef Sibik[15], Katalin Szitár[16], Koenraad Van Meerbeek[17], Laura Daco[11], Magda Boudagher[18], Marcin Klisz[19], Margareta Walczak[20], Marianne Evju[21], Martina Lužnik[1], Michael Kiehn[22], Murat Sarginci[23], Necmi Aksoy[23], Nihan Koçer[24], Oz Barazani[25], Paulina Anastasiu[26], Peter Stroh[27], Petr Vit[12], Philippine Vergeer[28], Radosław Puchałka[29], Rhea Kahale[18], Sandrine Godefroid[30,31,32], Sandro Lanfranco[33], Taras Parpan[34], Tiiu Kull[35], Valerijus Rašomavičius[36], Živa Fišer[1] & Peter Glasnović[1]✉

[1]University of Primorska, Faculty of mathematics, natural sciences and information technologies, Department of biodiversity, Glagoljaška 8, 6000, Koper, Slovenia. [2]Royal Botanic Gardens, Kew, Wellcome Trust Millennium Building, Wakehurst, Ardingly, West Sussex, RH17 6TN, United Kingdom. [3]Utrecht University Botanic Gardens, P.O. Box 80162, 3508 TD, Utrecht, Netherlands. [4]Laboratory of Biogeography & Ecology, Department of Geography, University of the Aegean, Mytilene, 81100, Greece. [5]Sociedade Portuguesa de Botânica, Travessa do Jardim, no.3, A-dos-Potes, 2615-018, Alverca do Ribatejo, Portugal. [6]Conservatory and Botanic Garden of the City of Geneva, Chemin de l'Impératrice 1, 1292, Chambésy, Switzerland. [7]Biology Department, Maynooth University, Co, Kildare, W23C2N1, Ireland. [8]Federal Agency for Nature Conservation, II 1.2 Plant Conservation, Konstantinstr. 110, 53179, Bonn, Germany. [9]University of Tirana, Faculty of Natural Sciences, Research Centre of Flora and Fauna, Blv Zog I, 25/1, Tirana, Albania. [10]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Via Torino 155, I-30172, Venice, Italy. [11]Musée national d'histoire naturelle, 25 rue Münster, L-2160, Luxembourg, Luxembourg. [12]Nature Conservation Agency of the Czech Republic, Kaplanova 1931/1, 148 00 Praha 11, Chodov, Czech Republic. [13]University of Latvia, Institute of Biology, Laboratory of Botany, Kronvalda bulvaris 4, LV-1010, Riga, Latvia. [14]Department of Genetics, Physiology and Plantations, Forest Research Institute, Bulgarian Academy of Sciences, 132, Kliment Ohridski Blvd, Sofia, 1756, Bulgaria. [15]Department of Biodiversity and Ecology, Plant Science and Biodiversity Center, Slovak Academy of Sciences, Institute of Botany, Dúbravská cesta 9, SK-845 23, Bratislava, Slovak Republic. [16]Landscape and Conservation Ecology Group, Institute of Ecology and Botany, HUN-REN Centre for Ecological Research 2-4 Alkotmány Str, Vácrátót, H-2163, Hungary. [17]Department of Earth and Environmental Sciences, KU Leuven, Celestijnenlaan 200E, 300, Leuven, Belgium. [18]Department of Life and Earth Sciences, Faculty of Science- Saint Joseph University, Mar Roukos, Dekwaneh, B.P. 1514, Lebanon. [19]Forest Research Institute, Department of Silviculture and Genetics of Forest Trees, Sękocin Stary, Poland. [20]Scientific Division, Israel Nature and National Parks Authority, 3 Am Ve'Olamo Street, Jerusalem, 95463, Israel. [21]Norwegian Institute for Nature Research, Sognsveien 68, NO-0855, Oslo, Norway. [22]Core Facility Botanical Garden, University of Vienna, Rennweg 14, 1030, Vienna, Austria. [23]Düzce University, Faculty of Forestry, Department of Forest Engineering, 81620, Düzce, Türkiye. [24]Düzce Univeristy, Vocational School of Forestry, Department of Forestry, 81620, Düzce, Türkiye. [25]Institute of Plant Sciences, Agricultural Research Organization, Volcani Institute, Rishon LeZion, 7505101, Israel. [26]University of Bucharest, Faculty of Biology, Department of Botany & Microbiology, Intr. Portocalelor 1-3, sector 6, 060101, Bucharest, Romania. [27]Botanical Society of Britain and Ireland (BSBI), Cambridge University Botanic Garden, 1 Brookside, Cambridge, UK. [28]Plant Ecology and Nature Conservation Group, Wageningen University, 6700 AA, Wageningen, The Netherlands. [29]Nicolaus Copernicus University in Toruń, Department of Ecology and Biogeography, Lwowska 1, 87-100, Torun, Poland. [30]Meise Botanic Garden, Nieuwelaan 38, 1860, Meise, Belgium. [31]Fédération Wallonie-Bruxelles, Service général de l'Enseignement supérieur et de la Recherche scientifique, rue A. Lavallée 1, 1080, Brussels, Belgium. [32]Université libre de Bruxelles, Laboratory of Plant Ecology and Biogeochemistry, CP 244, Boulevard du Triomphe, 1050, Brussels, Belgium. [33]University of Malta, Department of Biology, Msida, MSD2080, Malta. [34]Ukrainian Research Institute of Mountain Forestry, Department of Ecology and Forest Protection, Hrushevskoho 31, 76018, Ivano-Frankivsk, Ukraine. [35]Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Kreutzwaldi 5, Tartu, 51006, Estonia. [36]Nature Research Centre, Institute of Botany, Žaliųjų Ežerų 47, 12200, Vilnius, Lithuania. [37]These authors contributed equally: Nina Lončarević, Udayangani Liu. ✉e-mail: peter.glasnovic@upr.si