SafeNet: A European database of plant-pollinator interactions

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Abstract

Motivation: Pollinators play a crucial role in maintaining Earth's terrestrial biodiversity and human food production by mediating sexual reproduction for most flowering plants. However, their diversity and role as pollinators are increasingly compromised by rapid human-induced environmental changes. One of the major challenges for pollinator conservation, is the lack of robust generalisable data across space and time to comprehend the conservation status and population trends among different pollinator species. Here, we present the SafeNet database, a fully reproducible European-level database containing harmonized taxonomic data on plant-pollinator interactions referenced in both space and time. This database offers an open workflow that allows researchers to track decisions and edit them according to their preferences, while also providing other ecological variables of interest. We hope this database can help researchers to: 1) identify taxonomic, ecological and geographical gaps of knowledge on plant-pollinator interactions; and 2) explore the impacts of global change to guide future conservation planning for both plant and pollinator species.

Main Types of Variables Included: SafeNet contains 1,144,370 interactions between plants and pollinators from 51 different studies distributed across 17 European countries. In addition, information about sampling methodology, habitat type, bio-climatic region and further taxonomic rank information for both plant and pollinator species are also provided.

Spatial location and grain: The database contains 1,147 different sampling locations from natural and anthropogenic habitats that fall in 5 different bio-climatic regions. All records are geo-referenced and presented in the World Geodetic System 1984 (WGS84).

Time period and grain: Species interaction data was recorded between 2004 and 2021. All records are time-referenced and most of the studies documented interactions in a single flowering season (68.63%).

Major taxa and level of measurement: The database contains interaction data at the species level for 94.72% of the records, including a total of 1,353 plant and 2,065 pollinator species. The database covers 5.34% of the European species of flowering plants. The main focus of this database are insect pollinators and accounts for 33.82% of bees, 26.21% of butterflies and 33.08% of syrphids species at the European level.

Software format: The database was built with R software and is stored as ".rds" and ".csv" formats. The construction of the database is fully reproducible and can be accessed at the following PERMANENT LINKS.

KEYWORDS

plant-pollinator interactions, flowering plants, Angiosperms, pollinators, Hymenoptera, Diptera, Lepidoptera, Coleoptera, Europe

1 | INTRODUCTION

The interaction between plants and pollinators is one of the most well-documented mutualisms on Earth. Plant-pollinator interactions involve a great diversity of species, largely attributed to their coevolutive history (Ollerton 2017), and are critically important for terrestrial biodiversity and the human economy. The synergistic effects of climate change with other global change pressures are threatening worldwide biodiversity (Sala et al. 2000; Bellard et al. 2014), including plant and pollinator species as well as their interactions (González-Varo et al. 2013; Settele, Bishop, and Potts 2016; Eichenberg et al. 2021). Under this scenario, the increasing availability of biodiversity data plays a major role in our ecological understanding of species and guiding conservation planning (Heberling et al. 2021). However, our knowledge of plant and pollinator species and their network of interactions still exhibits major temporal, spatial and taxonomic biases (Archer et al. 2014; Troia and McManamay 2016; Poisot et al. 2021; Marshall et al. 2024), limiting our ability to effectively protect their biodiversity.

Europe is one of the continents with a larger amount of available biodiversity data (Proença et al. 2017), yet still exhibits major gaps (Wetzel et al. 2018; Bennett et al. 2018). While species checklists need to be treated carefully, especially at a macro-ecological scale (Grenié et al. 2023), the growing number of European plant and pollinator checklists along with occurrence data, is setting a foundation for the conservation of its flora and their pollinators. However, species richness is just one component of biodiversity and documenting the interaction between plants and pollinators is essential for understanding the fate of the species within an ecosystem (Jordano 2016). Numerous works have studied plant-pollinator interactions in the last decades, originating thousands of plant-pollinator interaction networks worldwide. Several initiatives have tried to integrate plant-pollinator interaction data into databases such as *Mangal* (Poisot et al. 2016) or *GloBI* (Poelen, Simons, and Mungall 2014), resulting in numerous large scale comparative analyses that enhanced our understanding of the ecology of plants and pollinators (e.g., European wild bee data trends; Marshall et al. 2024). Despite all these resources, Europe lacks accessible harmonized plant-pollinator interaction data that allow researchers to evaluate the state of the art of plant-pollinator interactions at European level, which will guide research efforts, conservation planning and will set a foundation for future global change research.

The interactions between different plant and pollinator species within a community form complex networks. Macro-ecological analyses of the topology of these networks have revealed common properties across them, such as truncated power-law degree distributions (Jordano 1987) or nestedness (Bascompte et al. 2003), and has added relevant information of their interaction ecology of plant-pollinator networks across geographic regions (Olesen and Jordano 2002; Traveset et al. 2016) and environmental gradients (Ramos-Jiliberto et al. 2010; Rech et al. 2016; Saunders et al. 2023). Although macro-ecological approaches make significant contributions to knowledge, they tend to be rare, and are strongly influenced by the spatio-temporal availability and nature of the data (Burkle and Alarcón 2011; Trøjelsgaard and Olesen 2013). For instance, plant-pollinator studies tend to differ in sampling effort and methodology which can impact the structure of the resulting plant-pollinator networks (Gibson et al. 2011; Jor-

dano 2016). Further, despite little sampling effort could capture most of the relevant functional species (Hegland et al. 2010), most plant-pollinator networks have unobserved interactions because undersampling (Olesen et al. 2011; Chacoff et al. 2012). Thus, the lack of strong spatio-temporal coverage along the current intrinsic limitations of sampling plant-pollinator networks, highlight the need of keep gathering and integrating informative species interaction data to properly unravel the different ecological processes at large scales.

Here, we present the SafeNet database, an acronym derived from the European project Safeguard and plant-pollinator networks, which contains harmonized informative interaction data of plants and pollinators at European level. The primary focus of the pollinator taxonomic groups is on the main orders of entomofauna that visit and pollinate flowering plants in Europe. These include insect species from the orders Hymenoptera, Diptera, Lepidoptera, and Coleoptera (Potts et al. 2015), which comprise almost the totality of recorded interactions in the SafeNet database (99.88%). SafeNet aims to cover a wide range of taxonomic groups and habitats while also provides other variables of interest that allow to better control for the ecological context and sampling methods. In addition, SafeNet offers a transparent and accessible workflow of its data management and species harmonization that allow to being reused and keep building on it over time. We expect that this database will help to evaluate macro-ecological processes and current gaps of plant-pollinator interactions at European level.

2 | METHODS

Data acquisition

This database is the result of one of the working packages of the European project Safeguard. The SafeNet database includes published and unpublished studies compiled initially by a wide number of researchers and institutions within the European continent. Data acquisition followed a non-systematic approach. First, data was directly asked to members of the Safeguard project and then, the request was extended to data owners outside of the project. These other studies were identified by direct communication with other colleagues and by directly searching studies on Google Scholar of under-represented regions of countries within the database. To keep high quality standards that will allow robust future ecological research, we only included: 1) studies that contained time- and geo-referenced records of plant-pollinator interactions; 2) studies with phyto-centric plant-pollinator networks with quantitative visitation data. The database contains 51 independent published and unpublished studies conducted during the time period 2004 - 2021 on 17 different countries (**Figure 1a** and **Figure 1b**).

Dataset description

SafeNet includes a total of 1,144,370 distinct interactions, considering interaction as the contact of a given pollinator to the reproductive structure of a particular plant, from 2,065 pollinator and 1,353 plant species. The majority of plant and pollinator species tend to be regionally specific, with only a minor portion of them being shared across a broad range of studies (**Figure 1b**). These different studies differ in sampling effort and methodology, although most studies took place within a single flowering season (68.63%), sampled a given location an average of 7.22 days, and documented interactions mostly by using transects as sampling method (62.75%).
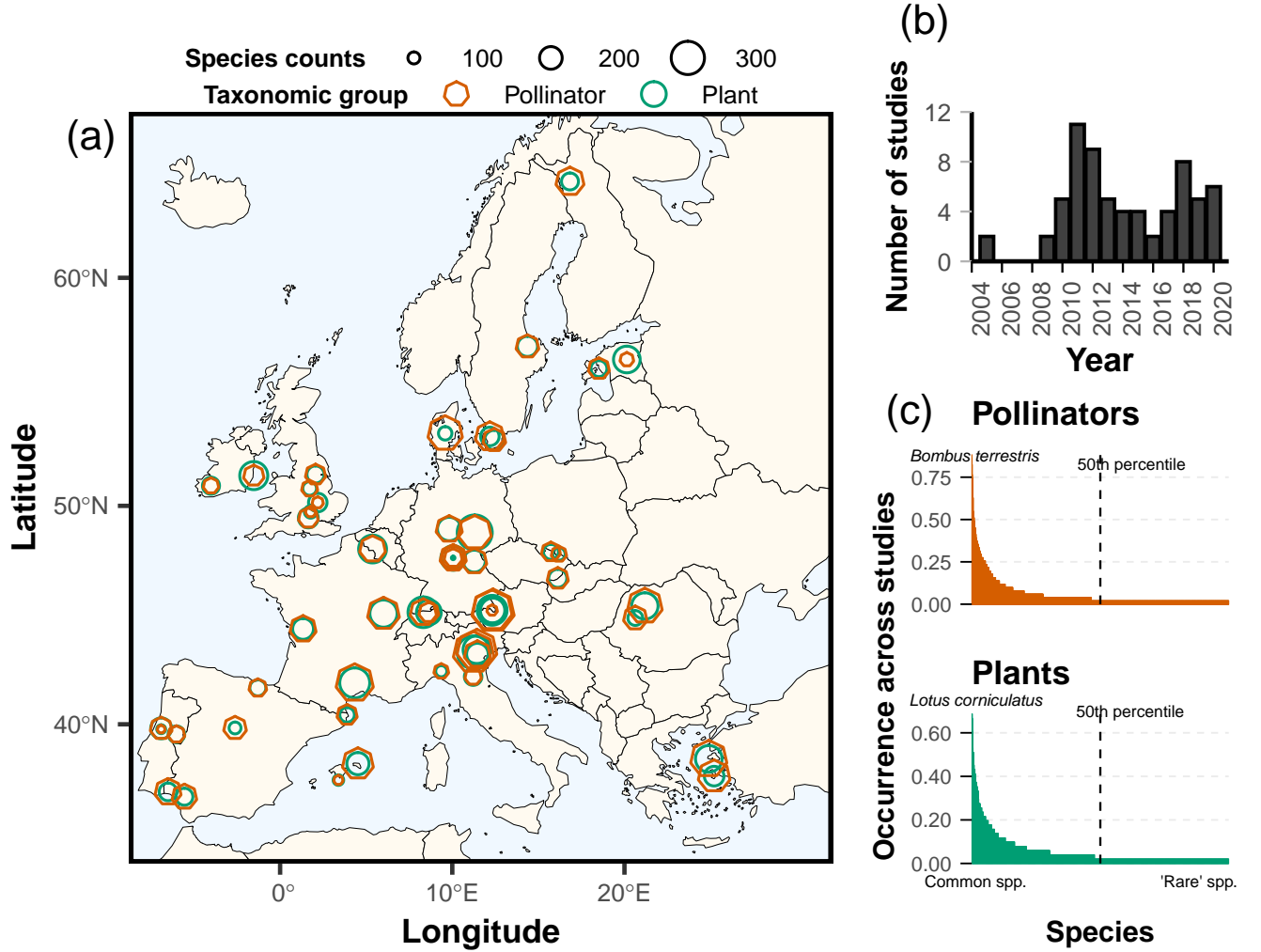
Figure 1. (**a**) Approximate locations of the studies of the SafeNet database showing the total number of pollinator (i.e., orange heptagon) and plant (i.e., green circles) species per study. The sizes of these shapes are proportional to the respective species counts. For visualization purposes, we have focused only on the European region with studies and selected a single location per study. (**b**) Number of studies by year within the database. (**c**) Percentage of shared occurrences of pollinators and plants across studies. Species on the left are highly shared across studies, while species on the right are found only in a few or a single study. As a reference, we have indicated the 50th percentile with a black dashed vertical line.

Data structure

The SafeNet database is available in both .csv and .rds formats. The .csv file contains data in long format, while the .rds file stores the data in a list structure, with networks organized within each study. The data is organized in three different files named interaction data, flower count data and metadata. The interaction file contains 30 columns that depict where and when the plant-pollinator interaction was observed (**Table 1**). To provide a standard unit of plant-pollinator interaction across studies, each row depicts a single interaction between a plant and a pollinator species. To build a plant-pollinator network matrix at a site level, authors only need to group interactions by plant and pollinator species, site and study. In addition, information about habitat type and bioclimatic region are also provided in this file. The floral count file contains measurements of floral availability and the unit of measurement, and should be merged with the interaction file by using the old plant name provided by the authors, site, and date if available. Only xxxx% of studies contain floral count information. The metadata file contains […]

Taxonomic harmonization

All plant and pollinator species names were checked and standardized according to large scale taxonomic databases. To ensure reproducibility of the workflow, we have conducted this harmonization in R with **rgbif** (Chamberlain, Oldoni, and Waller 2022) as pivotal package to check for species names and retrieve further taxonomic information (i.e., phylum, order, family and genus) from the Global Biodiversity Information Facility (GBIF). The protocol for plants and pollinators is similar but slightly different given the availability of the different taxonomic resources. For transparency, we have included in the database the old species name, the new assigned name, and, if name of the species is uncertain (e.g., species complex or species alike).

For plants: (i) we initially verify exact matches with the GBIF species checklist; (ii) select unmatched cases and fix orthographic errors; (iii) retrieve again taxonomic information for those unmatched cases, evaluate accuracy of fuzzing matching and programmatically fix records that are still not found; (iv) finally, we used the World Flora Taxonomic Backbone (Govaerts et al. 2021; WFO, July 7, 2022) as the ultimate filter for taxonomic information as we used it to calculate the plant taxonomic coverage of our database.

For pollinators: (i) we first created a checklist of species names for the most representative pollinator groups at European level by combining the recently published checklists of bees (Ghisbain et al. 2023), syrphids (Kočić et al. 2023) and butterflies (Wiemers et al. 2018); (ii) then, we compared pollinator species names against the checklist and recovered some unmatched cases with restrictive fuzzy matching by using **stringdist** package (Van der Loo et al. 2014); (iii) we programmatically fixed unmatched records when necessary and retrieved the taxonomic information for all species from GBIF; (iv) we fixed the non-found cases in the

Table 1.

Variable	Description
Study_id	Identifier of the study
Network_id	Identifier of a site sampled within a study
Sampling_method	Type of plant-pollinator sampling
Authors_habitat	Type of habitat as described by the authors
SafeNet_habitat	Type of habitat homogenized across studies
Bioregion	European biogiographical regions
Country	Country where the plant-pollinator interaction was observed
Locality	Locality where the plant-pollinator interaction was observed
Latitude-Longitude	Coordinates of the observed interaction in decimal degrees
Date	Year, month and day when the observation took place
Interaction	Number of interactions. By default is 1 as interactions are provided ungrouped
Plant_old_name	Plant species name given by the authors
Plant_accepted_name	Harmonized plant species name in the database
Plant_rank	Taxonomic rank of the observation
Plant_order	Order taxonomic rank of the observed plant species
Plant_family	Family taxonomic rank of the observed plant species
Plant_genus	Genus taxonomic rank of the observed plant species
Plant_unsure_id	Category to indicate if the plant species name is unsure (Yes) or not (No)
Plant_uncertainty_type	If the name is unsure, type of species uncertainty is provided
Pollinator_old_name	Pollinator species name given by the authors
Pollinator_accepted_name	Harmonized pollinator species name in the database
Pollinator_rank	Taxonomic rank of the observation
Pollinator_order	Order taxonomic rank of the observed pollinator species
Pollinator_family	Family taxonomic rank of the observed pollinator species
Pollinator_genus	Genus taxonomic rank of the observed pollinator species
Pollinator_unsure_id	Category to indicate if the pollinator species name is unsure (Yes) or not (No)
Pollinator_uncertainty_type	If the name is unsure, type of species uncertainty is provided
Flower_data	Floral data availability (Yes) or (No)
Flower_data_merger	Column to merge floral data with the interaction dataset

GBIF checklist and made sure that all species names from bees, syrphids and butterflies were named according to their respective species checklists.

Taxonomic coverage

To assess the completeness of plant and pollinator species in the SafeNet database at European level, we used the aforementioned checklists for plants and pollinators. Specifically for plants, we refined the checklist to include only European flowering plants and excluded taxonomic groups not associated with biotic pollination. We did this by first excluding the families considered to have exclusively a wind pollination mode (see Culley, Weller, and Sakai 2002), and then by filtering out the genera with wind or non-biotic pollination from families that exhibit both biotic and non-biotic pollination modes. Additionally, we manually included some exotic species and added unresolved species names that were not present in the accepted names of the checklist at the current version of usage. For pollinators, we compared only the taxonomic coverage of bees, syrphids and butterflies by using their species checklists at European level.

Habitat type and bioclimatic region

The different sites per study were classified with a habitat type by the authors. As these habitats are not standardized across studies, they were standardized with the additional help of land cover information and visual checks on current satellite imagery. For each georeferenced site, the land cover information was extracted from Corine Land Cover (CLC, version 2018) with the help of the Terra package (Hijmans et al. 2022). Based on the habitat classification from the authors and the CLC classification, we created habitat categories that intend to summarize the diversity of habitats in the SafeNet database (see habitat type definition in supplementary material). These categories allow a quick comparison and understanding of the habitat types from the database. However, we advise authors to revise this classification if they intend to rely on this field for their analyses as this is a non-fully objective process. Moreover, Europe is characterized by a great variety of environmental conditions that harbor different biota. Thus, to allow authors to explore set of studies that share similar environmental conditions and species, we assigned to each site a biogeographical region. The biogeographical regions were downloaded from the European Environment Agency (version 2016) and were matched to the different sites with the help of a spatial joint from the **sf** package (Pebesma et al. 2018).

3 | RESULTS

Taxonomy and taxonomic coverage

Provide number of species per taxonomic group and number of interactions Something always of interest: provide % of interactions of *Apis mellifera*?

phylogenetic and geographical biases
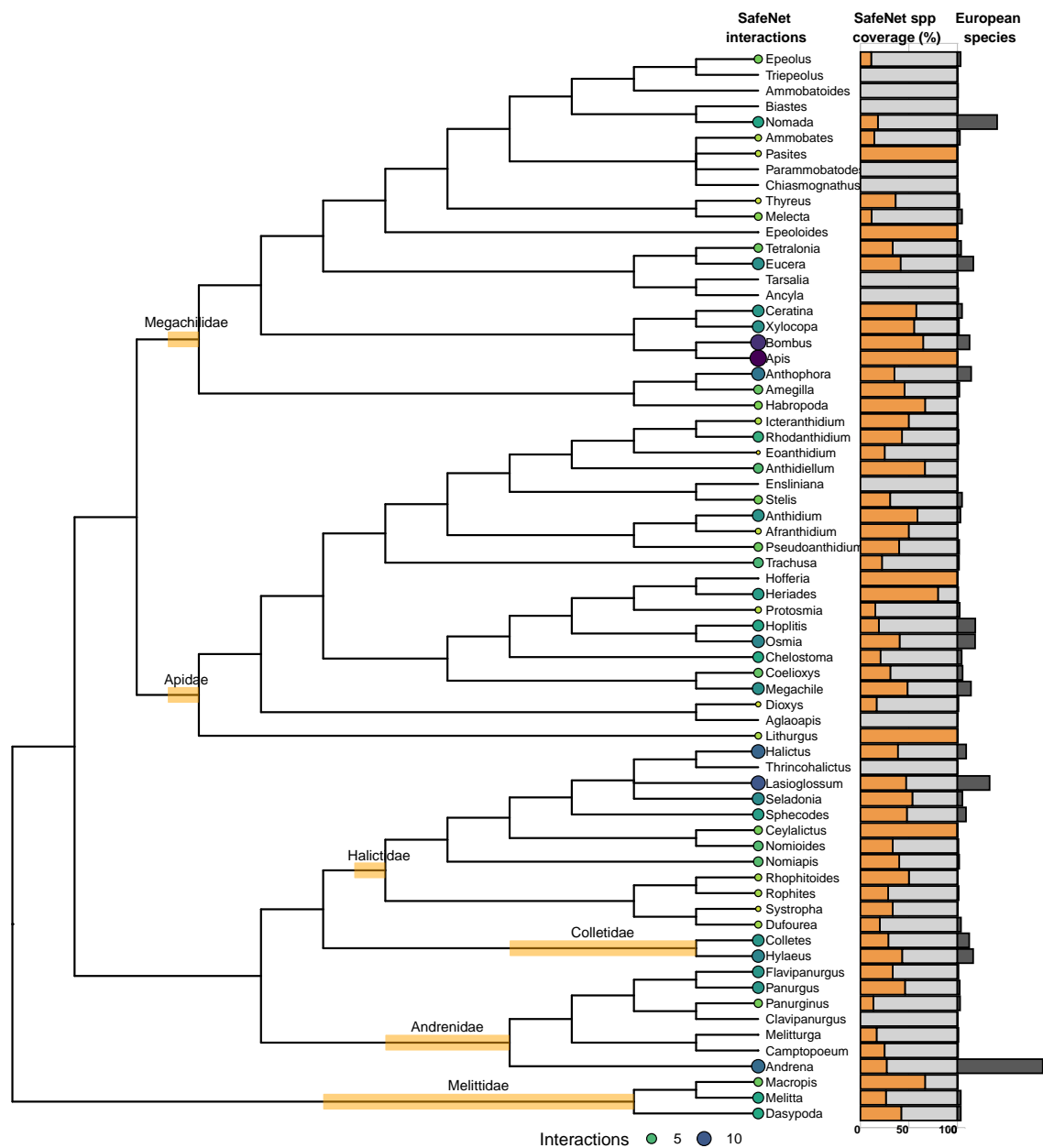
Figure 2. Phylogenetic representation of bee genera in the SafeNet database within the context of all European bee genera. The number of interactions recorded per genus in the database is illustrated using circles, with their sizes proportional to the number of interactions on a logarithmic scale. Additionally, a gradient of colors ranging from yellow to dark purple aids in this visualization. The coverage of species recorded in SafeNet per genus at the European level is depicted with orange and light grey bars, representing the percentage of species included and not included in the database, respectively, out of the total number of bee species per genus at the European level. Grey bars indicate the total number of species per genus at the European level.
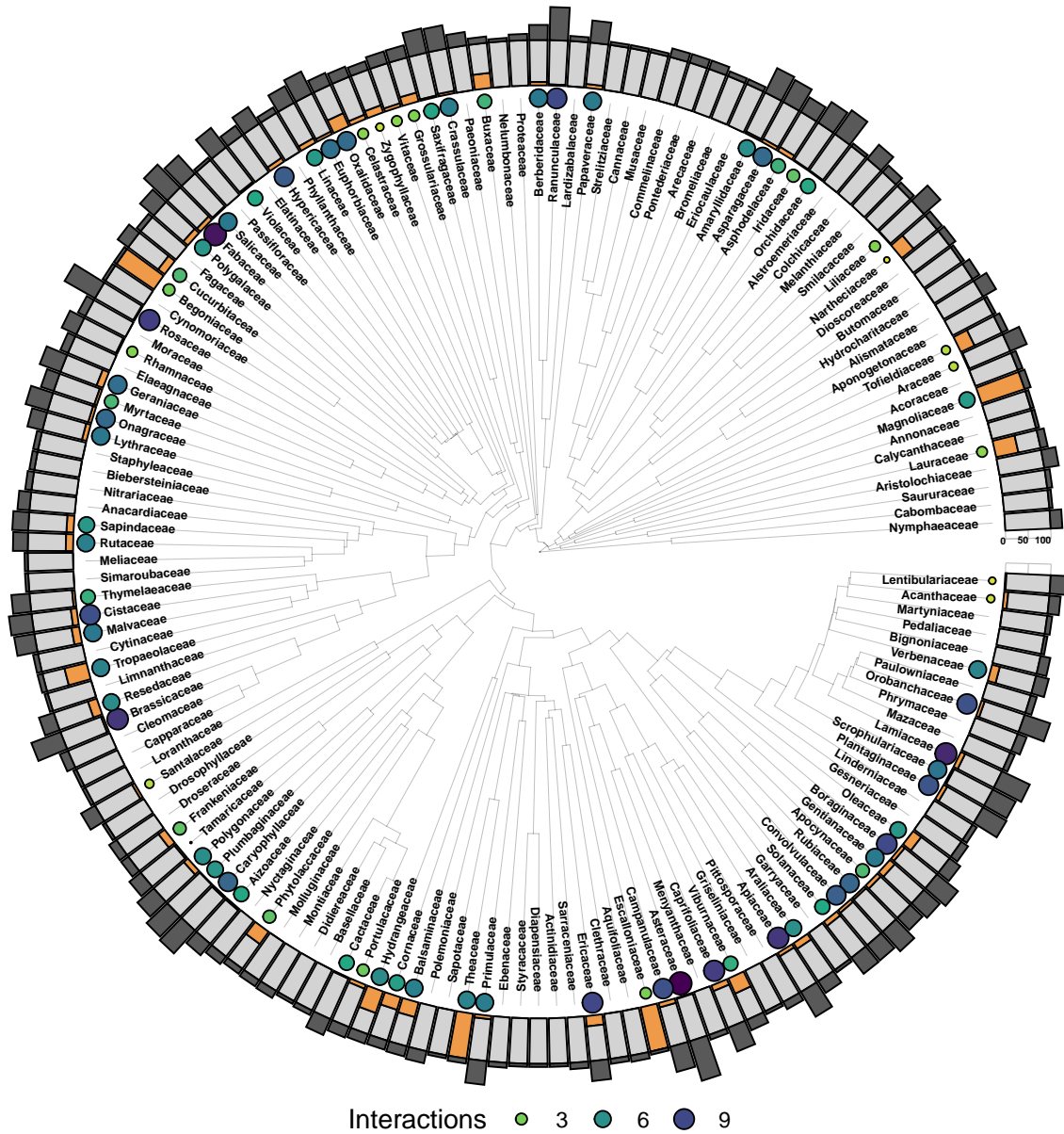
Figure 3. Phylogenetic representation of the plant families in the SafeNet database within the context of all flowering plant families occurring in Europe. The number of interactions recorded per genus in the database is illustrated using circles, with their sizes proportional to the number of interactions on a logarithmic scale. Additionally, a gradient of colors ranging from yellow to dark purple aids in this visualization. The coverage of species recorded in SafeNet per genus at the European level is depicted with orange and light grey bars, representing the percentage of species included and not included in the database, respectively, out of the total number of flowering plant species per family at the European level. Grey bars indicate the total number of species per family at the European level on logarithmic scale.

Habitat type and bioclimatic region

FIGURE 5? CLIFFHANGER OF NETWORK METRICS
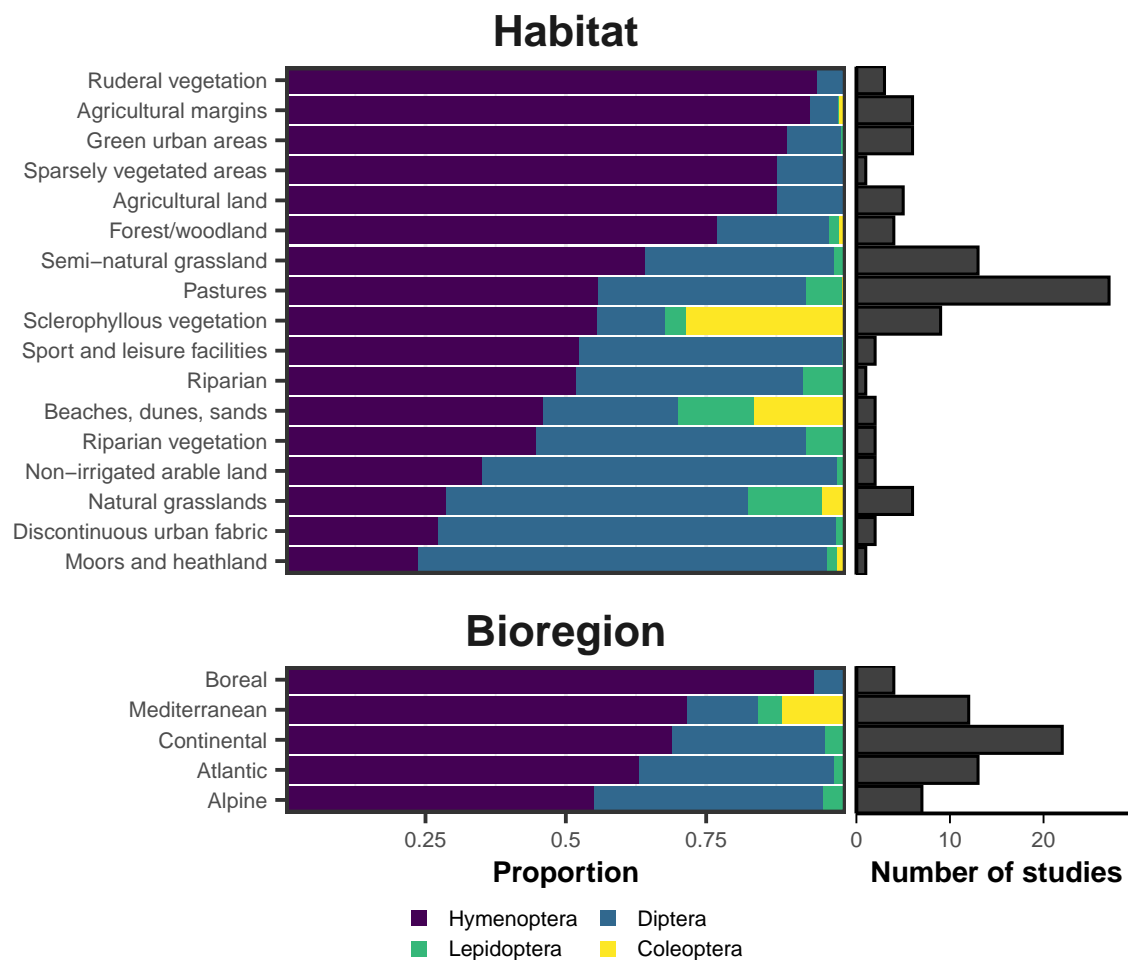
Figure 4. Proportion of the major pollinator orders by habitat types and bioclimatic regions in the SafeNet database. The orders, from left to right, include Hymenoptera, Diptera, Lepidoptera and Coleoptera. The horizontal barplot on the right indicates the number of studies that were conducted on each habitat type or bioclimatic region. Note that a single study can countribute to more than one habitat or bioclimatic region. Areas with a greater number of studies are more likely to depict accurate proportions of the different pollinator orders in those systems.

3 | DISCUSSION

Geographic and taxonomic biases!

Contextualise European diversity of plant and pollinator species with global biodiveristy

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Author contributions

Supplementary material

Supplementary text 1

Habitat definitions:

1) **Ruderal vegetation**: Plants growing on highly disturbed sites such as road sides or mineral extraction sites.

2) **Agricultural margings**: Sides of crops that can include any type of vegetation from low growing plants to trees.

3) **Green urban areas**: Parks, private gardens or small pastures within an urban setting. Botanical gardens are included in this category.

4) **Agricultural land**: Includes any type of crop and any type of vegetation growing within them.

5) **Forest/woodland understory**: Any plant community sampled under a wooded group of plants. The forest could be embedded in an agricultural setting or in a fully natural scenario. We have included here agro-forestry areas and open to dense forest. Note that we have excluded from this category forest that contains sclerophyllous vegetation.

6) **Semi-natural grassland**: Low growing plant community with relatively low disturbances but under low pressure such as seasonal mowing or extensive grazing.

7) **Pastures**: Any type of low growing plant community that is highly influenced by human disturbance. For instance, agriculture, mowing, moderate to high grazing or urban environments. Note that this category also includes old pastures with regrowth of woody vegetation.

8) **Sclerophyllous vegetation**: Any type of system with a dominant shrub community adapted to drought. Typical of the Mediterranean region. Note, that we have include in this category also woodlands (open coniferous forest) where the shrub community was the main focus of the study.

9) **Beaches, dunes, sands**: Plant communities growing on sandy soil.

10) **Riparian vegetation**: Plant communities growing on river margins.

11) **Natural grassslands**: Low growing plant communities with little or none human disturbance. Often located in high elevation areas within Europe.

12) **Moors and heathland**: Low growing woody vegetation characteristic from low fertile soils near the coast or in alpine areas.
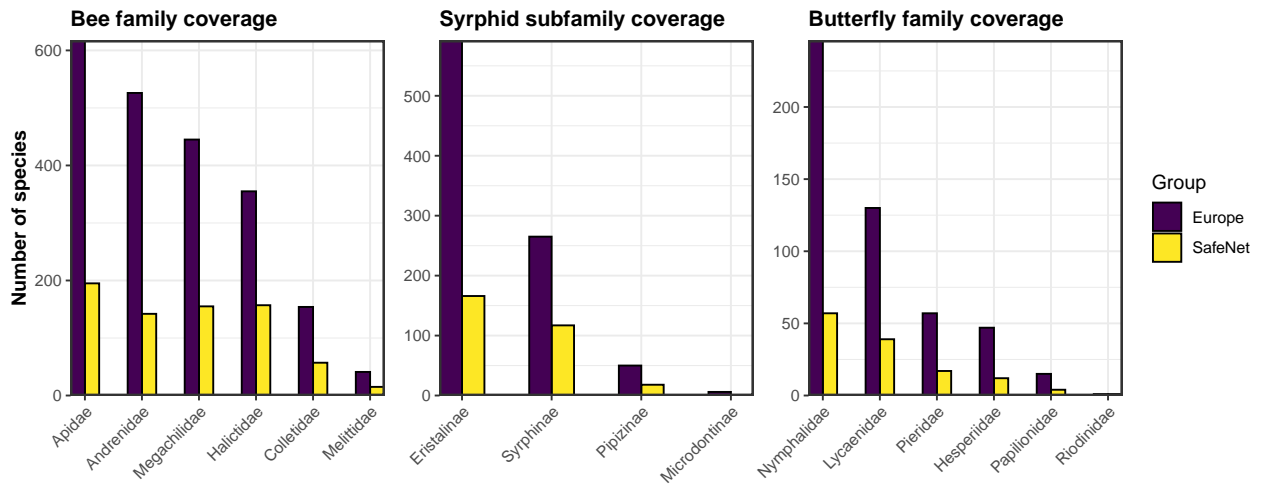
Figure S1. Coverage of the SafeNet species for bees (family level), syrphids (subfamily level) and butterflies (family level) in relation to the total number of European species within these taxonomic groups.