LegacyVegetation 1.0: Northern Hemisphere reconstruction of vegetation composition and forest cover from pollen archives of the last 14 ka

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Abstract. With rapid anthropogenic climate change future vegetation trajectories are uncertain. Climate-vegetation models can be useful for predictions but need extensive data on past vegetation for validation and improving systemic understanding. Even though pollen data provide a great source of this information, the data is compositionally biased due to differences in taxon-specific relative pollen productivity (RPP) and dispersal.

Here we present a Northern Hemisphere reconstruction of quantitative regional vegetation cover from a sedimentary pollen data set for the last 14 ka using the REVEALS model to correct for taxon- and basin-specific biases. For the reconstruction, we expanded on a previously published synthesis of continental RPP values.

The data sets include taxonomic compositions as well as reconstructed forest cover for each original pollen sample. 80% pollen sources areas were calculated for large lakes and are included in the data set. Additional metadata includes modeled ages, age model sources, basin locations, types and sizes.

The improvements in forest cover reconstructions with the REVEALS reconstruction using continental RPP values range from 24% (North America) to 72% (Europe) relative to the mean absolute error (MAE) of the pollen-based reconstruction. The dataset can be used as a grid with binned and aggregated samples (adjustable script provided on Zenodo; https://zenodo.org/doi/10.5281/zenodo.12800290) or as individual timeseries if the record's basin size exceeds 50 ha.

This improved quantitative reconstruction of vegetation cover is beneficial for the investigation of past vegetation dynamics and modern model validation. By collecting more RPP estimates especially in North America and adding more records to existing pollen data syntheses, reconstructions may be improved even further. The REVEALS reconstruction is freely available on PANGAEA (see Data availability section).

1 Introduction

Anthropogenic climate change is driving vegetation shifts that could lead to disruptions in ecosystem functions and services, and even trigger feedback effects with other earth system elements (IPCC, 2023; Armstrong McKay et al., 2022). Predicting these changes through modeling is challenging. A sufficient mechanistic understanding of vegetation dynamics and interactions with climate is needed, which requires validation and testing of model data with extensive vegetation data across climatic transitions comparable to those anticipated in the future (Dearing et al., 2012). Given the relatively brief duration of available instrumental climate and vegetation data, there is a clear need for long-term vegetation records derived from paleoecological archives that cover broader climatic gradients than modern datasets (Dearing et al., 2010; Dallmeyer et al., 2023).

Pollen data as a direct proxy for paleo-vegetation is especially useful for comparisons with modeled data as it can be used to reconstruct land-use (Fyfe et al., 2015; Davis et al., 2015), biomes (Woodbridge et al., 2014; Prentice et al., 1996), and climate (Herzschuh et al., 2023a, b; Bartlein et al., 2011; Viau et al., 2012). The compilation of pollen data syntheses is essential to aid this purpose (Anderson et al., 2006; Gaillard et al., 2010; Strandberg et al., 2014). Several subcontinental and continental collections of pollen data already exist, spanning regions such as Europe, North America, Africa, Siberia, and China (Fyfe et al., 2009a; Whitmore et al., 2005; Vincens et al., 2007; Cao et al., 2014, 2020) and have been integrated into the global database Neotoma (Williams et al., 2018). To allow for a broader application of pollen data, LegacyPollen 2.0 (Li et al., 2024b) offers a global, harmonized pollen dataset that underwent taxonomic standardization, metadata verification and consistent age modeling (Li et al., 2022a, 2021; Herzschuh et al., 2022). This taxonomic harmonization trades off higher taxonomic resolution of some datasets for equivalence, resulting in overall comparability useful for analyses at large spatial scales. Despite advances in harmonization, the use of pollen data remains limited due to the fact that pollen compositions do not accurately reflect vegetation (Davis, 1963; Prentice, 1985; Prentice and Webb III, 1986). This limitation arises from variations in taxon-specific parameters such as relative pollen productivity (RPP) and pollen dispersal characteristics, leading to discrepancies between the pollen record and actual past vegetation. This hinders quantitative vegetation assessment as taxa with high pollen productivity and efficient pollen dispersal tend to be overrepresented in the pollen record, while those with low pollen productivity and less effective dispersal are underrepresented. These factors, together with the compositional nature of pollen data, result in a non-linear relationship between pollen and vegetation (Prentice and Webb III, 1986). Approaches such as the R-value model (Davis, 1963; Webb et al., 1981) and the extended R-value model (Parsons and Prentice, 1981) were created to address this issue and were refined with Sugita's (2007) model for "Regional Estimates of Vegetation Abundance from Large Sites" (REVEALS) . By accounting for taxon-specific RPP and fall speed values, as well as basin-specific parameters such as basin size and type, REVEALS models quantitative vegetation cover in the region surrounding a basin from pollen compositions. The model has been applied in several regional-scale studies (Nielsen et al., 2012; Mazier et al., 2015; Hellman et al., 2008) and multiple validations have demonstrated its ability in approximating actual vegetation (Sugita et al., 2010; Hellman et al., 2008; Soepboer et al., 2010; Mazier et al., 2012), even though the model's performance heavily relies on accurate taxon-specific parameters. While Wieczorek and Herzschuh (2020) and Githumbi et al. (2022)provide a comprehensive compilation of RPP and fall speed values for taxa of the Northern Hemisphere, the overall availability of RPP studies is still limited and regional variations in RPP values exist (Harris et al., 2020; Broström et al., 2008; Li et al., 2017; Mazier et al., 2012). This makes the application of REVEALS on larger scales particularly challenging. Only some (sub-) continental REVEALS reconstructions are available for Europe (Trondman et al., 2015; Roberts et al., 2018; Githumbi et al., 2022; Serge et al., 2023), Asia (Cao et al., 2019; Li et al., 2022b, 2023, 2024a), and North America (Dawson et al., 2024). Currently, no global or Northern Hemispheric quantitative vegetation cover reconstructions using REVEALS exist.

With its importance for the assessment of biome stability, carbon storage, climatic feedbacks, and land-use-change, forest cover is an often reconstructed variable (e.g. Fyfe et al., 2015; Githumbi et al., 2022; Serge et al., 2023). Due to the global availability of remote sensing data on contemporary forest cover, it also offers good opportunities for the validation of reconstructions (Hjelle et al., 2015; Roberts et al., 2018). Yet, only Serge et al. (2023) and Pirzamanbein et al. (2014) use this opportunity for extensive validation and even improvement of reconstructions from European pollen records. No grid-cell based validations exist for the Northern Hemisphere.

Here we present reconstructed quantitative vegetation cover for the Northern Hemisphere from the LegacyPollen2.0 dataset - an updated global taxonomically and temporally standardized fossil pollen dataset of 3680 palynological records - using REVEALS spanning the last 14k years. The data sets were created using existing estimates of taxon-specific parameters. The REVEALS reconstruction includes corrected vegetation compositions as well as reconstructed forest cover.

2 Methods

2.1 Pollen Data Set

The pollen data synthesis LegacyPollen2.0 (Li et al., 2024b) includes 3680 temporally resolved records (time-series) distributed globally. Data were collected from individual publications and the Neotoma Paleoecology Database which includes data from the European Pollen Database, the QUAVIDA data base for Australasia, the Latin American Pollen Database, the African Pollen Database and the North American Pollen database (Flantua et al., 2015; Fyfe et al., 2009b; Giesecke et al., 2014; Lézine et al., 2021; Rowe et al., 2007; Whitmore et al., 2005; Williams et al., 2018). An overview of Neotoma records included in LegacyPollen 2.0 and this reconstruction can be found in S1.

Sediment and peat cores used for the creation of pollen data are of lacustrine, peat and marine origin. For the REVEALS reconstruction only lake and peat records in the Northern Hemisphere were used (n = 2732) Analogous to the preceding LegacyPollen 1.0 dataset (Herzschuh et al., 2022), the data synthesis involved revising age modeling and taxonomic harmonization for consistency of records. Spatial data coverage of records in the reconstruction is dense in Europe (1275 records) and North America (1016 records) and sparsest in Asia (441) (see Fig. 1). The records' sample density decreases with age (see Fig. 2).

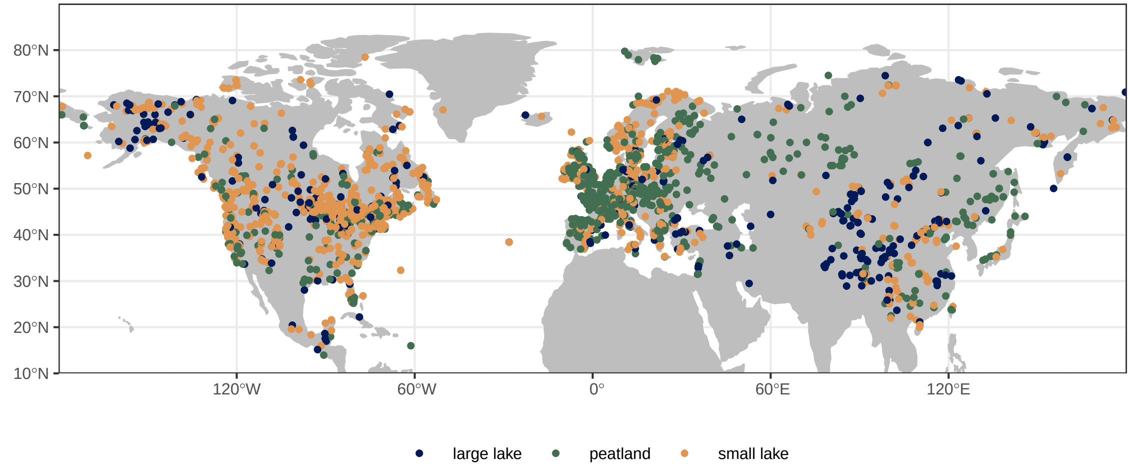

Figure 1. Pollen record locations in the LegacyVegetation dataset. Colors indicate record type (large lake $\geq$ 50 ha). Record density is highest in Europe and Eastern North America, and lowest in Northern and Central Asia.

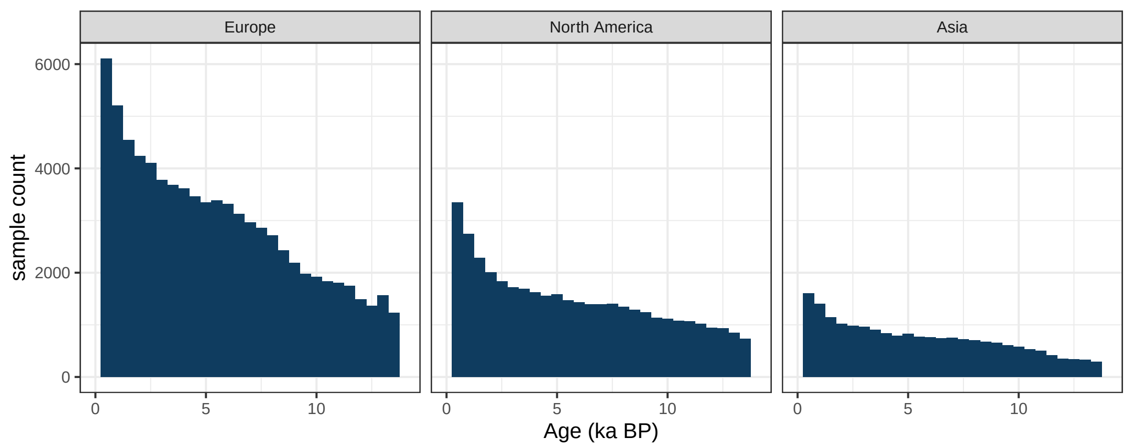

Figure 2. Temporal coverage of records in the LegacyVegetation dataset per continent. Bins are 500 years wide. Sample count decreases with age and Europe has the most samples overall.

2.2 Implementing REVEALS

The REVEALS model ("Regional Estimates of Vegetation Abundance from Large Sites") estimates quantitative vegetation coverage from pollen assemblages using site and taxon-specific parameters (Sugita, 2007). Based on wind speed and taxon-specific fall speed, pollen dispersal is modeled in ring sources around the basin and deposition over the basin is integrated to give pollen influx. Together with RPP this dispersal factor is used to correct original pollen counts to better represent actual vegetation (see Equation 1 and Table 1). By running the model with variations of relative pollen productivity (RPP) values, a statistical distribution of results is calculated.

$$\hat{V}_i = \frac{n_{i,k}/\hat{\alpha}_i \int_R^{Z_{max}} g_i(z)dz}{\sum_{j=1}^{m}(n_{j,k}/\hat{\alpha}_j \int_R^{Z_{max}} g_i(z)dz)} \quad (1)$$

The REVEALS model follows a set of assumptions. Firstly, neither directionality nor pollen transport through agents other than wind are considered in the model. Additionally, it is assumed that the basin is circular with no source of pollen within the basin radius. The peatland and bog sites used in our reconstructions inherently violate this assumption. Nevertheless, the quantitative reconstruction of vegetation cover from peatland cores is possible by using Prentice's deposition model (Prentice, 1985, 1988) instead of Sugita's deposition model (Sugita, 1993) in the dispersal and deposition function (see Eq. 1; Sugita, 2007). Previous studies show that results from small bogs are still reliable when aggregated, while results from large bogs tend to deviate from those of large lakes (Trondman et al., 2015; Mazier et al., 2012; Trondman et al., 2016). Using peatland records for reconstructions is, therefore, appropriate when spatially averaging multiple sites. We use the implementation of REVEALS from the R package REVEALSinR (Theuerkauf et al., 2016). For further details on the REVEALS model see the original publication Sugita (2007) or Githumbi et al. (2022).

Table 1. Algebraic terms in the REVEALS equation (see Equation 1)

Function term	definition
$\hat{V}_i$	vegetation estimate of taxon i
$n_{i,k}$	pollen counts of taxon i at site k
α_i	relative pollen productivity of taxon i
R	basin radius
Z_{max}	maximum extent of regional vegetation
z	distance from a point in the center of a basin
g_i	dispersal and deposition function for taxon i

2.2.1 Parameters and Model Settings

For each taxon, values for RPP (with uncertainties provided as standard deviation) and fall speeds are used. We made use of the synthesis of Northern Hemisphere RPP and fall speed values by Wieczorek and Herzschuh (2020). Several RPP studies published since this synthesis were added to the compilation (Geng et al., 2022; Li et al., 2022b; Wang et al., 2021; Huang et al., 2021; Zhang et al., 2021a, b; Wan et al., 2020, 2023; Jiang et al., 2020). The methods by Wieczorek and Herzschuh (2020) were followed fore study selection and calculation of synthesis values. An overview of original values and synthesized values can be found in Appendix A and B respectively.

When available, we use continent-specific values in our reconstruction. For taxa with no continental values present, we use Northern Hemispheric values. If no values exist for a taxon, RPP is set to a constant (RPP = 1, σ=0.25) and fall speeds are filled with mean continental fall speeds. Continental RPP values are available for the majority of pollen counts in all three continents (see Fig. 3). The fraction of pollen counts for which standard RPP values were assumed is highest in North America but still $< 10\%$. For each site, the REVEALS model also requires information on basin type, basin size and original pollen counts, all of which were collected in the LegacyPollen 2.0 dataset (Li et al., 2024b). Apart from taxon- and basin-specific parameters the REVEALS model requires several constant parameters to be set, which can be found in Table 2.

Table 2. Static model parameters and model settings for REVEALS runs using REVEALSinR (Theuerkauf et al., 2016).

Parameter	Values and settings used in model run
atmospheric model	unstable atmosphere
dispersal model	gaussian plume
wind speed	$3m \times s^{-1}$
maximum extent of regional vegetation (region cutoff)	1000 km
number of RPP variations	2000
peatland basin radius	100 m
function to randomize pollen counts	rmultinom_reveals

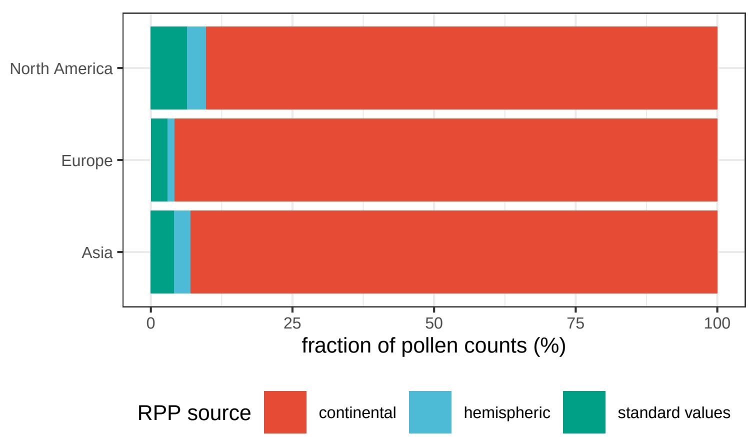

Figure 3. Regional source of RPP values for percentage of pollen counts per continent. A majority of pollen counts is covered by continental RPP values with the highest fraction in Europe. Only a small percentage of pollen counts has only hemispheric RPP values available. No available RPP values lead to the use of a standardized RPP value of 1 ± 0.25.

2.2.2 Modifications in REVEALSinR

We calculate the radius of the 80% pollen source area by finding the radius in which the median influx of all taxa is 80% of the total influx (as defined by the total influx in the maximum extent of regional vegetation chosen). This is calculated by employing the lake deposition model in REVEALSinR (Theuerkauf et al., 2016). Starting from z_{max} the deposited pollen is calculated per taxon. This is assumed to be the total pollen each taxon deposits. In a step-wise process the radius around the basin is increased and the deposited pollen relative to the total influx at z_{max} is calculated for each taxon. We define our 80% pollen source radius as the radius where the median of the relative influx of all taxa reaches 80%. The primary objective of this calculation is to provide a clear understanding of the scale of the source area for users unfamiliar with pollen data. It highlights the regional nature of lacustrine pollen data and demonstrates the influence of lake size on this source area.

We also reduced computational effort in REVEALSinR by implementing a maximum number of steps in the lake model used to model mixing in the basin. The number of steps was set to 500 unless n falls below that maximum value for $n = basin\,radius/10$ for basins with a radius of at least 1000 m and $n = basin\,radius/2$ for basins with a radius smaller than 1000 m.

2.3 Reconstruction of forest cover and validation

Forest cover was reconstructed by summing up percentages of arboreal taxa (see S2: List of arboreal taxa) with Betulaceae, *Betula*, and *Alnus* being classified as arboreal at sites below 70° N. The mean reconstructed compositional coverages from the REVEALS results were used for the forest cover reconstructions. REVEALS results were then rasterized to aggregate and include records from smaller basins as well. Reconstructed time series were averaged in 500 year bins and then rasterized in grids of differing spatial resolution. A grid cell was classified as having a valid reconstruction when it contained records from at least one large lake (>= 50 ha) or at least two small basins following Serge et al. (2023). Standard deviations of the REVEALS estimates were aggregated by applying the delta method by Stuart and Ord (1994), using the same equation as Wieczorek and Herzschuh (2020). We provide a script for rasterization with adjustable temporal and spatial resolution for users of the dataset on Zenodo (https://zenodo.org/doi/10.5281/zenodo.12800290). For validation, the reconstructed forest cover of the past 100 years was rasterized and compared to modern remote sensing forest cover. Only valid grid cells as defined above were used for validation. Average tree canopy cover for all grid cells was extracted from the Landsat Global Forest Cover Change (GFCC) data set from the temporal average of the years 2000, 2005, 2010 and 2015 (Sexton et al., 2013; Townshend, 2016). An openness correction was applied to sites containing urban areas and paved surfaces within the 80% pollen source areas (PSA) to correct for areas without any pollen sources and thus ensure comparability to modern remote sensing forest cover (see Equations 2-4). For this, the percentage of unvegetated land cover classes for the year 2015 in the ESA CCI land cover data set was used (ESA, 2017, see Table 3). Areas covered by water or ice are already considered as missing values in the remote sensing forest cover data set and do not need to be corrected for. Forest cover was validated for each grid cell and mean absolute error (MAE) and correlation coefficients calculated for each continent. No openness correction was applied to the reconstruction values in the final dataset. Validation for a 2x2° grid is included in the results section. Further validations using 1°,5°, and 10° resolution are included in the supplementary material (S3: Validation results for different spatial resolutions).

Table 3. Unvegetated land cover classes in ESA CCI LC chosen for the openness correction.

Name	Code
Urban areas	190
Bare areas	200
Consolidated bare areas	201
Unconsolidated bare areas	202

$$unvegetated\,classes = \{190, 200, 201, 202\} \tag{2}$$

$$unvegetated\,(\%) = \frac{\sum cells\ in\ PSA \in unvegetated\,classes}{\sum cells\ in\ PSA} \tag{3}$$

$$corrected\,tree\,cover = reconstructed\,tree\,cover \times (1 - unvegetated) \tag{4}$$

3 Data summary

3.1 80% Pollen Source Areas

Using REVEALS, radii of 80% pollen source areas were calculated for large lakes(see Fig. 4). The radii indicate in which area 80% of the deposited pollen originated from (see Section 2.2.2) and yield an understanding of which area the pollen record is representative of, which is especially useful when individual time series from large lakes are being used for analyses. The 80% pollen source areas are roughly a function of basin size (see Fig. 5) and range between 155 km and 762 km. The median 80% pollen source radius is 225 km including all large lakes.

3.2 Reconstructed compositions

REVEALS was used to reconstruct quantitative vegetation cover. Here we compared these reconstructed compositions to the original pollen composition. Differences in composition between Pollen data and REVEALS are apparent for all continents of the Northern Hemisphere. Some clear examples include: increases of Cyperaceae in all continents, decreases of Betula in

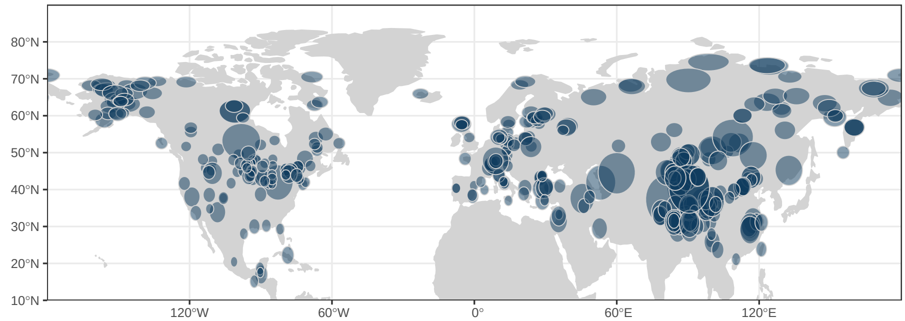

Figure 4. Map indicating the relevant pollen source areas for large lakes. Many small basins in Europe lead to smaller 80% pollen source areas. Several large basins and correspondingly large 80% pollen source areas exist in Asia. In general the 80% pollen source areas highlight the regional nature of the pollen record signal.

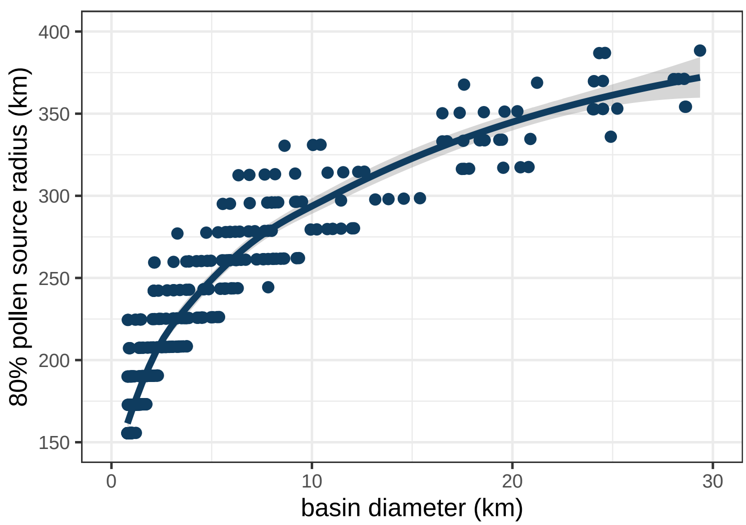

Figure 5. Scatterplot of basin diameter and 80% pollen source area of large lakes in the REVEALS data set. In general, larger basins have larger pollen source areas with the relationship between diameter and 80% pollen source radius being roughly logarithmic.

Europe, decreases of Pinus in all continents, and increases of Acer in North America with the application of REVEALS and its intended correction of taxon-sepcific biases (see Fig. 6).

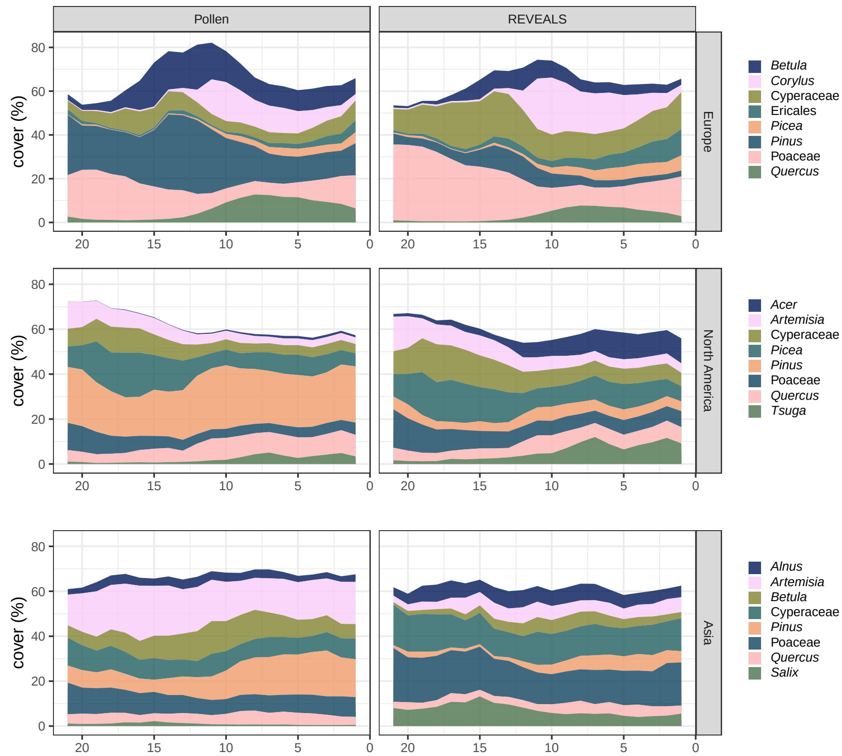

Figure 6. Average continental taxonomic coverages per reconstruction for the 8 most common taxa per continent. Differences are especially evident for Pinus, Artemisia, and Betula, which all have decreased coverages after the application of REVEALS, as well as Poaceae and Cyperaceae with increased coverages.

3.3 Reconstructed forest cover

Using the compositional data available from the original pollen data and the REVEALS run, we reconstructed forest cover for all sites and samples and rasterized the result with different spatial resolutions. The temporal trend in Northern Hemisphere forest cover is the same for both reconstructions. Forest cover increases from 14 ka BP until roughly 6 ka BP and decreases again towards the present (see Fig. 7). REVEALS reconstructed forest cover is generally lower than forest cover from original pollen compositions. On average forest cover values from the REVEALS run are roughly 14.54% lower than values from original pollen compositions. The temporal trends in Asia and North America are positive, whereas forest cover in Europe has its maximum around 6 ka BP and has been decreasing since.

Forest cover is generally highest in Eastern North America. This is also where data coverage is best in North America (see Fig. 8). Density of valid grid cells is very high in Europe, where forest cover increases until roughly 6 ka BP and then decreases. Data coverage in Asia is sparse, but valid grid cells indicate higher forest cover on the Southeastern coast and in the boreal biome. Rather open areas exist at the Tibetan Plateau and at very high latitudes. The forest cover derived from the REVEALS

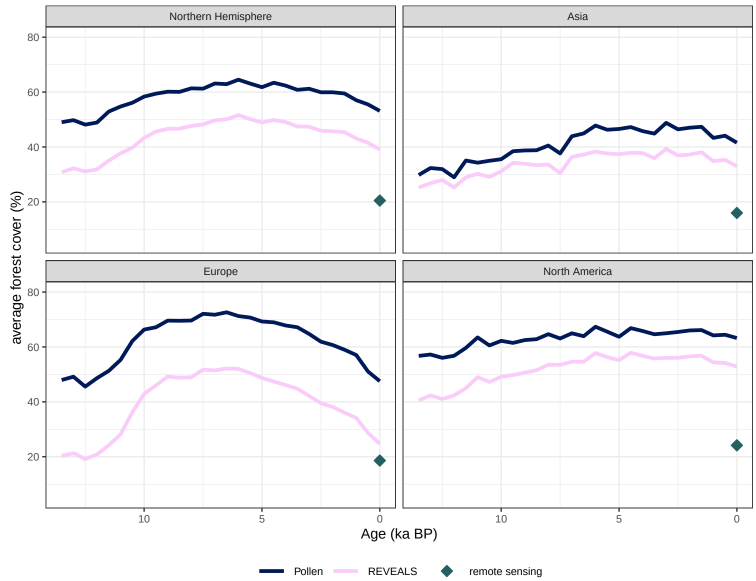

Figure 7. Northern Hemisphere and continental average forest cover from 2x2° grid cell means for raw pollen data and the REVEALS reconstruction (Northern Hemisphere and continental averages from different grid cell resolutions are available in S2: Reconstruction results for different spatial resolutions). Remotely sensed global average forest clover for the grid cells with valid pollen coverage is indicated with the diamond. Temporal trends are the same, but absolute forest cover is reduced in the REVEALS reconstructions compared to the original pollen data. Both reconstructions still overestimate forest cover.

reconstruction is generally lower. However, the difference between Pollen and REVEALS forest cover is smaller in North America than in Europe and Asia.

3.4 Validation with gridded data sets

Remote sensing forest cover within relevant pollen source areas was used to validate the modern, reconstructed forest cover from the original pollen data and the REVEALS run for each grid cell. Here we present validation of gridded data with a 2° spatial resolution. Validations with additional spatial resolutions differ only marginally and are included in the supplementary materials (S3: Validation results for different spatial resolutions). Forest cover reconstructed from original pollen data is predominantly higher than remote sensing forest cover with a mean absolute error (MAE) of 33.05% in the Northern Hemisphere (see Fig. 10a). As reconstructed forest cover is much lower for the REVEALS reconstruction (see Fig.7), the MAE value is reduced significantly to 19.73% (see Fig. 9a).

Continental mean absolute errors (MAE) in forest cover from original pollen data range from 24.61% (Asia) to 37.49% forest cover (North America, see Fig. 9b). All continental MAE values are lower for the REVEALS reconstruction and range from 9.44% (Europe) to 27.27% (North America). The improvement is largest in Europe (72% relative to the initial MAE

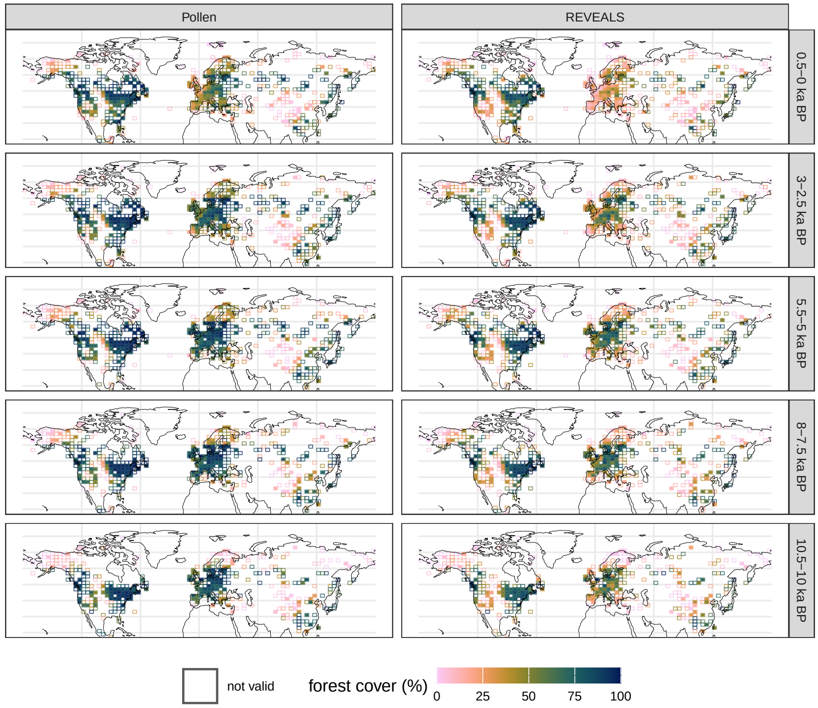

Figure 8. Reconstructed forest cover in 2x2° grid cells from raw pollen data and the REVEALS reconstruction for 5 example time slices (reconstructions with different grid cell sizes are available in the in S2: Reconstruction results for different spatial resolutions). Valid cells are filled and include reconstructions from at least one large lake (≥ 50 ha) or several smaller basins. Forest cover in Eastern North America is higher than in Europe and Asia. REVEALS reconstructed forest cover is generally lower than raw pollen reconstructions.

of the pollen-based reconstruction, see Fig. 9 and 10) and smallest in North America (24%). REVEALS reconstructed forest cover also has higher correlation coefficients in all continents. The REVEALS run, therefore, produced reconstructed forest cover that corresponds better remote sensing forest cover. Nevertheless, forest cover still tends to be overestimated.

Spatial patterns are present for the errors of both forest cover reconstructions (see Fig. 11). In Europe the REVEALS reconstruction manages to reduce errors extensively. In Eastern and coastal Northwestern North America, the REVEALS reconstruction still tends to overestimate forest cover. This could be due to a lack of continental RPP values. In North America, few RPP studies are available (see Appendix A) and more taxa are assigned hemispheric or standardized values than in the other continents.

The large difference between forest cover reconstructed from original pollen compositions and remote sensing forest cover could be due to the difference in the signal that is recorded. Remote sensing forest cover records the canopy, whereas pollen data also records the vegetation present below the tallest canopy. Several layers of trees could, therefore, increase the percent-

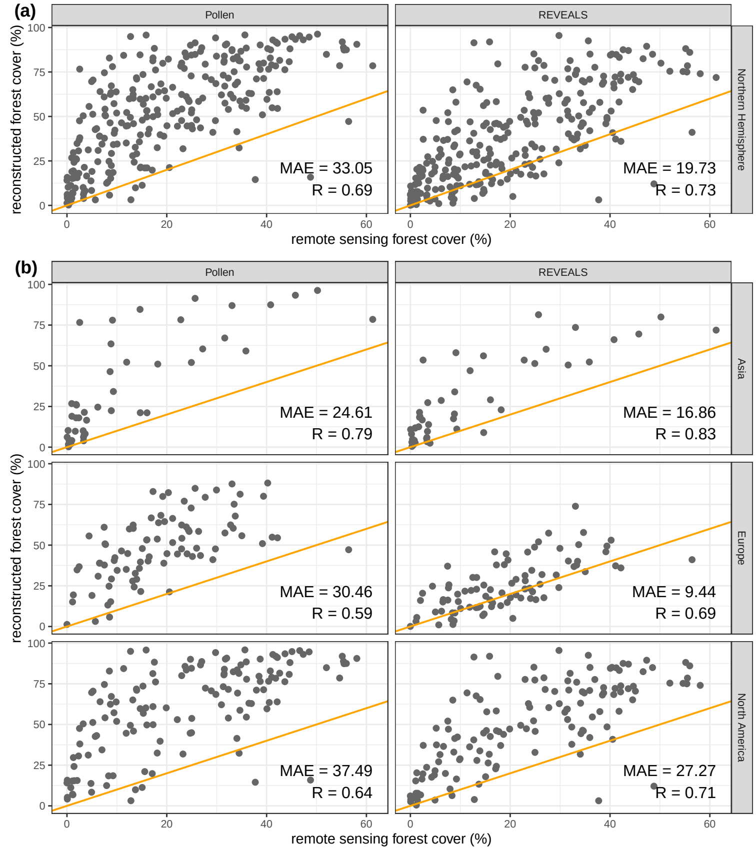

Figure 9. Remote sensing forest cover (LANDSAT) and modern reconstructed forest cover from Pollen and REVEALS (< 100 years BP) in 2x2° grid cells with mean absolute errors (MAE) and correlation coefficient (R) per group. Reconstructed forest cover from the original pollen data tends to overestimate observed (remote sensing) forest cover. Improvements with the REVEALS reconstruction are especially high in Europe. Validations with different grid cell sizes are available in the supplement (S3: Validation results for different spatial resolutions).

age of arboreal taxa recorded. Even though this comparison between these data sources may not be straightforward, it is still necessary for this large-scale validation of reconstruction as few other vegetation data is available globally. Additionally, it is more likely that the overestimation of forest cover in the initial pollen data is due to the higher production of pollen by trees than by non-arboreal taxa. This leads to an overrepresentation of arboreal taxa in the pollen record. By using REVEALS, the pollen productivity of taxa is taken into account and corrected for. The proportion of arboreal taxa is therefore strongly reduced in the vegetation compositions reconstructed using REVEALS.

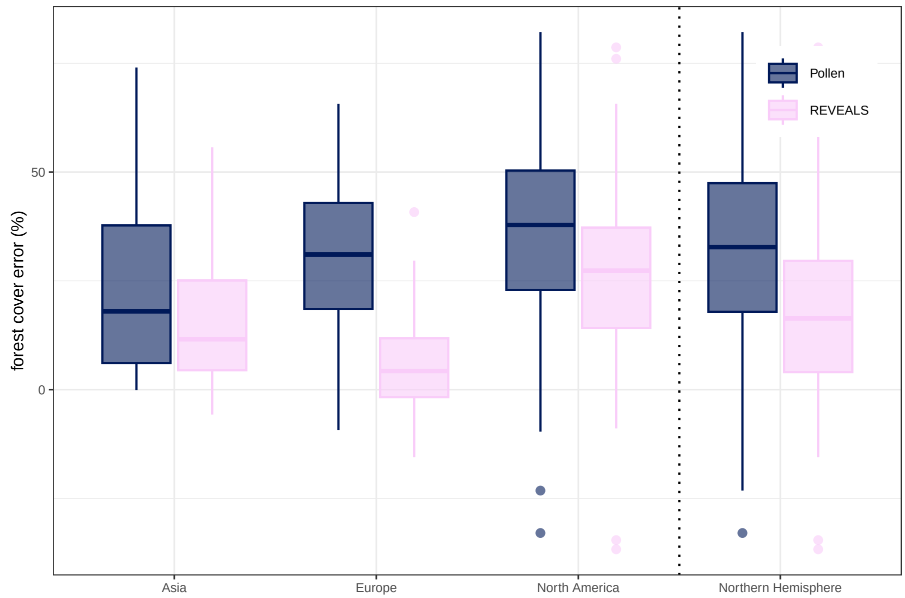

Figure 10. Forest cover reconstruction error per continent for a gridded 2x2° reconstruction. Mean errors decreased with the REVEALS reconstruction for all continents but are still generally > 0 (overestimation of forest cover). Lowest errors are present in Europe.

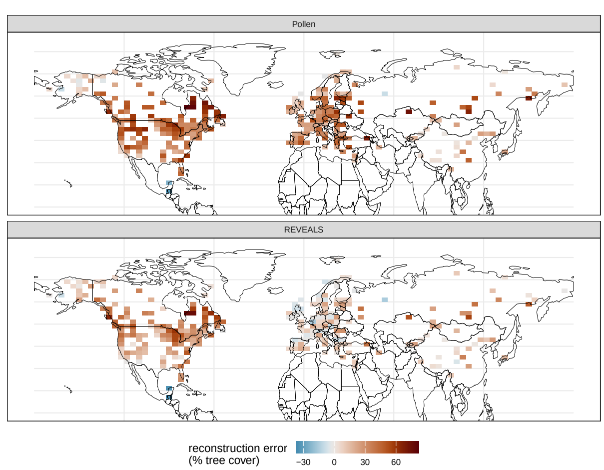

Figure 11. Map of the reconstruction error (in % forest cover) for forest cover reconstructed from Pollen and REVEALS data. Remaining errors with the overall better REVEALS reconstructions are especially high in North America (Northern West Coast, Labrador Peninsula).

4 Dataset applications and limitations

Our reconstructed quantitative vegetation cover datasets using REVEALS provide reconstructions of taxonomic compositions as well as forest cover in Europe, Asia, and North America and extend to 14 ka BP. The reconstructions made use of taxon-specific parameters and were, thus, able to correct some of the compositional biases present in pollen compositions. Notably, the error in modern reconstructed forest cover was reduced compared to pollen-based reconstructions on all continents which shows that improvements in forest cover reconstructions from REVEALS applications are considerable.

Reconstruction results are also similar to available large-scale pollen-based vegetation reconstructions. Increases in forest cover in northern and eastern Asia up until the Holocene thermal maximum as seen in our results are consistent with reconstructions by Cao et al. (2019) and Tian et al. (2016). The reconstructed spatial patterns of forest cover in China with low forest cover in the North China plain and the Tibetan Plateau and a higher forest cover along the east coast and the south agree with previous reconstructions as well (Li et al., 2023, 2022b, 2024a). Results for European forest cover also roughly correspond with previous REVEALS applications and show an increase of forest cover after the last glacial maximum until roughly 6 ka BP (Githumbi et al., 2022; Fyfe et al., 2015; Serge et al., 2023; Strandberg et al., 2023). The gridded reconstruction by Serge et al. (2023) was even validated with modern remote sensing forest cover and showed a good fit.

The REVEALS forest cover reconstructions presented here offer valuable insight into past vegetation changes. The global dataset provides an opportunity to explore past vegetation dynamics, gaining a deeper understanding of responses, trajectories, and potential feedback mechanisms. Given the increasing discussions surrounding the possibility of tipping events in vegetation cover (Armstrong McKay et al., 2022; Lenton and Williams, 2013), this could be of considerable use. While a reconstruction of exact tree lines is not trivial with pollen data, the application of REVEALS and subsequent biomization improve treeline reconstructions as shown by Binney et al. (2011). Additionally, this dataset can address unanswered questions about Holocene vegetation dynamics, including the deglacial forest conundrum (Dallmeyer et al., 2022; Strandberg et al., 2022). It also serves as a valuable tool for validating models with coupled climate and vegetation, which rely on extensive time series and vegetation data for accurate predictions (Dallmeyer et al., 2023; Dawson et al., 2024). Comparing modeled vegetation to reconstructed vegetation could help uncover missing dynamics in coupled climate-vegetation models. New insights gained from these applications could enhance our ability to predict future changes.

However, the reconstructions are associated with some of the limitations of sedimentary pollen data. This includes age uncertainty, temporal mixing, and irregular spatial and temporal resolution of records. Age uncertainty is already treated as best as possible through consistent age modeling of the pollen dataset (Li et al., 2022a, 2021). Nevertheless, in general, replicating sediment and peat cores could provide more accurate estimates. Moreover, there is uncertainty surrounding the success of the compositional reconstructions. As global compositional vegetation data is not readily available, using remote sensing forest cover poses as the best option for validation. Even with an accurate forest cover reconstruction, uncertainties persist regarding the abundance of individual taxa due to the aggregated nature of the forest cover measure. To address this, global syntheses of forest and other plant inventories or compositional remote sensing products could offer better validation. Another challenge lies in validating the results with past vegetation data. It is uncertain whether RPP values have remained stable over time, and historical compositional data are not only scarce but likely too recent to test this assumption (Baker et al., 2016). Vegetational compositions from sedimentary ancient DNA could provide a solution. Local aDNA vegetation signals could be averaged across multiple records within a pollen source area to generate a comparable reconstructed vegetation composition using a different proxy and to compare to pollen-based results (Niemeyer et al., 2017).

To ensure the correct utilization of the dataset and to obtain reliable analysis results, several key considerations should be followed. Firstly, rasterization mitigates individual errors by temporal and spatial averaging. This process is particularly useful in reducing the variance that might arise from individual measurements, providing a more reliable representation of the underlying signal.The reliability of reconstructions varies among different taxa due to the quality of RPP values, and this is explicitly documented in a supplementary file that outlines the sources of RPP values (see Section Code and Data availability). Reconstructions of taxa with continental RPP values are the most reliable, followed by those based on hemispheric data, with standardized RPP values being the least reliable. This hierarchy should be taken into account when interpreting the results. Higher certainty is associated with forest cover reconstruction, as it is based on aggregation among taxa. Reconstructions of temporal forest cover trends are reliable, as evidenced by high correlation coefficients, despite a tendency for absolute values to be overestimated, particularly in North America. For individual time series, the reliability of data varies with the size of the lakes from which samples were taken. Only data derived from large lakes ($\geq$ 50 ha) are reliable for site-wise analyses. This distinction is clearly indicated with validity flags in the dataset. Reconstructions from smaller basins should not be used alone.

5 Conclusions

We present data sets of reconstructed compositional vegetation and forest cover in the Northern Hemisphere from a sedimentary pollen data set using the REVEALS model. We used synthesized RPP values for reconstruction and made use of hemispheric or standardized values, when continental ones were not available. This approach allowed us to address some of the inherent biases in pollen compositions. Considerable improvement in the reconstruction of forest cover is achieved in all continents. Improvements were smallest in North America, which suggest a need for further RPP studies.

Accurate data on past vegetation is invaluable for the validation of coupled climate-vegetation models and the testing of hypotheses on feedback effects and vegetation dynamics. This knowledge is essential for modeling and predicting vegetation trajectories under anthropogenic climate change.

6 Code and data availability

The produced datasets are freely available from Zenodo (https://doi.org/10.5281/zenodo.12800159).

Input data from LegacyPollen 2.0 is available on PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.965907, Li et al. 2024b).

The code used to produce the datasets and adjustable rasterization code are freely available from Zenodo (https://doi.org/10.5281/zenodo.10191859, https://doi.org/10.5281/zenodo.12800291, Schild and Ewald 2023).

Appendix A: Original RPP values

Taxon	Continent	RPP	SE	reference	study DOI
Acer	Asia	0.0869	0.0621	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Alnus	Asia	0.85	1.53	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Amaranthaceae	Asia	21.01	2.47	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Amaranthaceae	Asia	3.57	0.81	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Amaranthaceae	Asia	0.18	0.16	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Amaranthaceae	Asia	5.379	1.077	Wang and Herzschuh 2011	https://doi.org/10.1016/j.revpalbo.2011.09.004
Amaranthaceae	Asia	7.72	1.47	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Amaranthaceae	Asia	21.35	2.34	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Amaranthaceae	Asia	28.39	1.62	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Amaranthaceae	Asia	27.9	2.9	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Amaranthaceae	Asia	10.6	0.6	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Amaranthaceae	Asia	7.72	1.47	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Amaryllidaceae	Asia	1.64	0.4	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Anacardiaceae	Asia	0.45	0.07	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Anacardiaceae	Asia	1.77	0.04	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Anacardiaceae	Asia	0.4478	0.0746	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Artemisia	Asia	19.33	0.41	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Artemisia	Asia	19.03	0.27	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Artemisia	Asia	24.7	0.36	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Artemisia	Asia	3.267	0.628	Wang and Herzschuh 2011	https://doi.org/10.1016/j.revpalbo.2011.09.004
Artemisia	Asia	21.53	2.16	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Artemisia	Asia	5.77	0.35	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Artemisia	Asia	3.4	0.18	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Artemisia	Asia	21.33	0.4	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Artemisia	Asia	16.15	1.41	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Artemisia	Asia	5.77	0.35	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Artemisia	Asia	1.81	0.3	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Asteraceae	Asia	7.73	0.54	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Asteraceae	Asia	1.26	0.4	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Asteraceae	Asia	0.86	0.11	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Asteraceae	Asia	3	0.32	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Asteraceae	Asia	1.1	0.12	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Asteraceae	Asia	8.85	0.51	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Asteraceae	Asia	20.5	2.68	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Asteraceae	Asia	8.15	0.45	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Asteraceae	Asia	1.8	0.2	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Asteraceae	Asia	3	0.32	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Asteraceae	Asia	8.74	0.05	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Asteraceae	Asia	0.31	0.25	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Betula	Asia	12.52	0.37	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Betula	Asia	13.16	0.08	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Betula	Asia	11.67	0.22	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Betula	Asia	7.8	0.51	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Betula	Asia	2.82	0.28	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Betula	Asia	1.59	5.86	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Betula	Asia	5.171	0.2259	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Betula	Asia	4.97	0.08	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Brassicaceae	Asia	0.89	0.18	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9

Brassicaceae	Asia	3.4	0.2	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Camellia	Asia	0.5832	0.0194	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Carpinus	Asia	1.5416	0.3029	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Caryophyllaceae	Asia	78.2	5.85	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Caryophyllaceae	Asia	0.87	0.14	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Caryophyllaceae	Asia	7.28	0.14	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Caryophyllaceae	Asia	25.75	2.35	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Caryophyllaceae	Asia	7.28	0.14	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Caryophyllaceae	Asia	11.86	0.87	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Castanea	Asia	11.49	0.49	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Castanea	Asia	0.25	0.01	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Castanea	Asia	0.2537	0.0149	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Castanopsis	Asia	19.44	0.17	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Convolvulaceae	Asia	0.18	0.03	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Corylus	Asia	3.17	0.2	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Corylus	Asia	3.17	0.2	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Cupressaceae	Asia	1.11	0.09	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Cyclobalanopsis	Asia	2.4106	0.1361	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Cyperaceae	Asia	8.9	0.33	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Cyperaceae	Asia	0.21	0.07	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Cyperaceae	Asia	0.66	0.021	Wang and Herzschuh 2011	https://doi.org/10.1016/j.revpalbo.2011.09.004
Cyperaceae	Asia	0.54	0.19	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Cyperaceae	Asia	0	0.0071	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Cyperaceae	Asia	0.016	4.86	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Cyperaceae	Asia	20.8	0.65	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Cyperaceae	Asia	1.6	0.12	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Cyperaceae	Asia	0.04	0.03	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Cyperaceae	Asia	0.5373	0.194	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Elaeagnaceae	Asia	8.88	1.3	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Elaeagnaceae	Asia	18.4	0.44	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Ephedraceae	Asia	22.87	0.76	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Ericaceae	Asia	1.57	0.2	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Ericaceae	Asia	1.57	0.2	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Euphorbiaceae	Asia	2.21	0.08	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Euphorbiaceae	Asia	5.22	0.1	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Fabaceae	Asia	0.2	0.1	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Fabaceae	Asia	0.78	0.03	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Fabaceae	Asia	0.21	0.07	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Fabaceae	Asia	0.2	0.1	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Fabaceae	Asia	0.209	0.0746	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Fraxinus	Asia	1.89	0.35	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Fraxinus	Asia	0.21	0.06	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Hippophae	Asia	18.38	1.27	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Humulus	Asia	16.3	1	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Ilex	Asia	6.7068	0.5832	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Juglandaceae	Asia	1.8955	0.0896	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Juglans	Asia	4.82	0.22	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Juglans	Asia	0.3	0.05	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Juglans	Asia	7.69	0.49	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Juglans	Asia	1.69	0.24	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Juglans	Asia	1.9	0.09	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Lamiaceae	Asia	0.2	0.13	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15

Lamiaceae	Asia	2.27	0.35	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Lamiaceae	Asia	1.9	0.3	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Larix	Asia	0.74	0.1	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Larix	Asia	3.87	0.6	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Larix	Asia	4.41	0.15	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Larix	Asia	0.2	0.06	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Larix	Asia	2.18	0.36	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Larix	Asia	6.61	3.5	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Liliaceae	Asia	1.49	0.11	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Liliaceae	Asia	2.45	0.4	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Liquidambar	Asia	2.255	0.1166	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Mallotus	Asia	10.8475	1.7107	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Malus	Asia	0.0869	0.0372	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Moraceae	Asia	6.52	0.08	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Papilionaceae	Asia	2.66	0.05	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Picea	Asia	29.4	0.87	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Picea	Asia	3.4	0.83	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Pinus	Asia	7.72	0.25	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Pinus	Asia	8.96	0.23	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Pinus	Asia	29.55	1.77	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Pinus	Asia	18.82	0.54	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Pinus	Asia	13.24	1.19	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Pinus	Asia	12.85	1.26	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Pinus	Asia	31.3	1.97	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Pinus	Asia	16.22	5.86	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Pinus	Asia	1.9637	0.0894	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Pinus	Asia	12.85	1.26	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Pinus	Asia	32.1	1.94	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Pinus	Asia	13.2388	1.194	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Poaceae	Asia	1	0	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Poaceae	Asia	1	0	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Poaceae	Asia	1	0	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Poaceae	Asia	1	0	Wang and Herzschuh 2011	https://doi.org/10.1016/j.revpalbo.2011.09.004
Poaceae	Asia	1	0	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Poaceae	Asia	1	0	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Poaceae	Asia	1	0.19	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Poaceae	Asia	1	0	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Poaceae	Asia	1	0	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Poaceae	Asia	1	0	Ge et al. 2017	https://doi.org/10.1016/j.scitotenv.2017.02.027
Poaceae	Asia	1	0	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Poaceae	Asia	1	0	Geng et al. 2022	https://doi.org/10.3389/fevo.2022.837857
Poaceae	Asia	1	0	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Poaceae	Asia	1	0	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Poaceae	Asia	1	0	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Poaceae	Asia	1	0	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Polygonaceae	Asia	26.35	1.85	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Potentilla	Asia	1.4	0.2	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Quercus	Asia	2.48	0	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Quercus	Asia	4.89	0.16	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Quercus	Asia	5.48	0.11	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Quercus	Asia	1.75	0.31	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Quercus	Asia	1.49	0	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197

Quercus	Asia	0.81	0.07	Zhang et al. 2020	https://doi.org/10.1007/s00334-020-00779-x
Quercus	Asia	0.6	0.08	Li et al. 2017b	https://doi.org/10.1007/s00334-017-0636-9
Quercus	Asia	0.81	0.007	Zhang et al. 2021a	https://doi.org/10.1007/s00334-020-00779-x
Quercus	Asia	2.69	0.08	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Ranunculaceae	Asia	7.86	2.65	Zhang et al. 2017	https://doi.org/10.11928/j.issn.1001-7410.2017.06.24
Rhododendron	Asia	2.48	0.27	Zhang et al. 2021b	https://doi.org/10.1016/j.ecolind.2021.107928
Rosaceae	Asia	0.22	0.09	Ge et al. 2015	https://doi.org/10.11928/j.issn.1001-7410.2015.04.15
Rosaceae	Asia	0.84	0.04	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Rosaceae	Asia	0.8358	0.0448	Jiang et al. 2020	https://doi.org/10.1002/jqs.3197
Rubiaceae	Asia	1.23	0.36	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Rubiaceae	Asia	1.29	0.02	Wan et al. 2020	https://doi.org/10.1016/j.ecolind.2020.106297
Salix	Asia	0.23	0.11	Geng et al. 2022	https://doi.org/10.1016/j.scitotenv.2017.02.027
Sanguisorba	Asia	24.07	3.5	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Symplocos	Asia	0.2138	0.0389	Wan et al. 2023	https://doi.org/10.1016/j.scitotenv.2017.02.027
Syringa	Asia	3.3936	0.216	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Tamaricaceae	Asia	1.5	0.13	Wang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.19
Thalictrum	Asia	2.8	0.4	Huang et al. 2021	https://doi.org/10.11928/j.issn.1001-7410.2021.06.18
Thymelaceae	Asia	33.05	3.78	Li et al. in prep (in Li et al. 2018)	https://doi.org/10.3389/fpls.2018.01214
Tilia	Asia	0.4	0.1	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Ulmus	Asia	3.48	0.87	Li et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.02.003
Ulmus	Asia	1	0.31	Li et al. 2017a	https://doi.org/10.1007/s00334-017-0636-9
Ulmus	Asia	1.5962	0.1539	Li M. et al. 2022	https://doi.org/10.1016/j.quaint.2022.03.010
Abies	Europe	9.92	2.86	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Abies	Europe	3.83	0.37	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Acer	Europe	0.32	0.09	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Acer	Europe	0.3	0.09	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Acer	Europe	0.07	0.01	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Alnus	Europe	2.56	0.32	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Alnus	Europe	8.74	0.35	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Alnus	Europe	19.96	1.6	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Alnus	Europe	15.95	0.6622	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Alnus	Europe	6.42	0.42	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Alnus	Europe	2.86	0.07	Niemeyer et al. 2015	https://doi.org/10.1177/0959683615596822
Amaranthaceae	Europe	4.28	0.27	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Apiaceae	Europe	0.26	0.01	Hjelle 1998	https://doi.org/10.1007/BF01373926
Apiaceae	Europe	0.21	0.03	Hjelle 1998	https://doi.org/10.1007/BF01373926
Apiaceae	Europe	5.91	1.23	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Artemisia	Europe	2.77	0.39	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Artemisia	Europe	5.89	3.16	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Asteraceae	Europe	0.06	0.004	Hjelle 1998	https://doi.org/10.1007/BF01373926
Asteraceae	Europe	0.1	0.01	Hjelle 1998	https://doi.org/10.1007/BF01373926
Asteraceae	Europe	0.05	0.02	Hjelle 1998	https://doi.org/10.1007/BF01373926
Asteraceae	Europe	0.09	0.02	Hjelle 1998	https://doi.org/10.1007/BF01373926
Asteraceae	Europe	0.24	0.06	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Asteraceae	Europe	0.17	0.03	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Asteraceae	Europe	0.16	0.1	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Asteraceae	Europe	0.68	0.06	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Asteraceae	Europe	0.65	0.06	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Asteraceae	Europe	0.28	0.04	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Betula	Europe	6.18	0.35	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Betula	Europe	4.6	0.7	Räsänen et al. 2007	https://doi.org/10.1016/j.revpalbo.2007.04.004
Betula	Europe	12.38	2.48	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z

Betula	Europe	13.94	0.2293	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Betula	Europe	1.8	0.26	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Betula	Europe	2.24	0.2	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Betula	Europe	2.42	0.39	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Betula	Europe	1.82	0.33	Niemeyer et al. 2015	https://doi.org/10.1177/0959683615596822
Brassicaceae	Europe	0.07	0.04	Kunes et al. 2019	https://doi.org/10.1177/095968361986202б
Carpinus	Europe	12.17	0.66	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Carpinus	Europe	4.48	0.0301	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Carpinus	Europe	4.56	0.85	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Carpinus	Europe	0.24	0.07	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Carpinus	Europe	0.1	0.01	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Cerealia	Europe	0.0462	0.0018	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Cerealia	Europe	0.75	0.04	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Cerealia	Europe	11.58	2.48	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Cerealia	Europe	5.25	1.24	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Cerealia	Europe	3.023	1.14	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Cerealia	Europe	0.22	0.12	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Corylus	Europe	1.51	0.06	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Corylus	Europe	1.35	0.0512	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Corylus	Europe	2.58	0.25	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Corylus	Europe	0.3	0.04	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Cyperaceae	Europe	0.29	0.01	Hjelle 1998	https://doi.org/10.1007/BF01373926
Cyperaceae	Europe	0.13	0.03	Hjelle 1998	https://doi.org/10.1007/BF01373926
Cyperaceae	Europe	0.53	0.06	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Cyperaceae	Europe	1	0.16	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Cyperaceae	Europe	0.89	0.03	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Cyperaceae	Europe	0.72	0.07	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Cyperaceae	Europe	0.11	0.075	Niemeyer et al. 2015	https://doi.org/10.1177/0959683615596822
Cyperaceae	Europe	0.77	0.05	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Ericales	Europe	1.1	0.05	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Ericales	Europe	0.07	0.06	Räsänen et al. 2007	https://doi.org/10.1016/j.revpalbo.2007.04.004
Ericales	Europe	0.01	0.01	Räsänen et al. 2007	https://doi.org/10.1016/j.revpalbo.2007.04.004
Ericales	Europe	1.07	0.03	Hjelle 1998	https://doi.org/10.1007/BF01373926
Ericales	Europe	0.33	0.03	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Ericales	Europe	4.69	0.7	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Ericales	Europe	0.11	0.03	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Ericales	Europe	0.07	0.04	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Ericales	Europe	0.3	0.03	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Fabaceae	Europe	0.4	0.07	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Fagus	Europe	5.09	0.22	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Fagus	Europe	7.5	0.58	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Fagus	Europe	0.76	0.17	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Fagus	Europe	1.2	0.16	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Fagus	Europe	0.06	0	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Fraxinus	Europe	1.11	0.09	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Fraxinus	Europe	0.7	0.06	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Fraxinus	Europe	8.67	0.87	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Fraxinus	Europe	1.39	0.21	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Fraxinus	Europe	2.99	0.88	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Juniperus	Europe	7.94	1.28	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Larix	Europe	11.29	2.33	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Larix	Europe	0.16	0.05	Niemeyer et al. 2015	https://doi.org/10.1177/0959683615596822

Picea	Europe	1.19	0.42	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Picea	Europe	2.04	0.36	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Picea	Europe	2.78	0.21	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Picea	Europe	0.57	0.16	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Picea	Europe	8.5	0.3	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Picea	Europe	0.36	0.02	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Pinus	Europe	6.17	0.41	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Pinus	Europe	8.4	1.34	Räsänen et al. 2007	https://doi.org/10.1016/j.revpalbo.2007.04.004
Pinus	Europe	7.29	0	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Pinus	Europe	23.12	0.2388	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Pinus	Europe	21.58	2.87	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Pinus	Europe	1.35	0.45	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Plantaginaceae	Europe	3.7	0.7	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Plantaginaceae	Europe	1.27	0.18	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Plantaginaceae	Europe	1.99	0.04	Hjelle 1998	https://doi.org/10.1007/BF01373926
Plantaginaceae	Europe	0.48	0.02	Hjelle 1998	https://doi.org/10.1007/BF01373926
Plantaginaceae	Europe	12.83	1.85	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Plantaginaceae	Europe	0.24	0.15	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Plantaginaceae	Europe	1.29	0.18	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Plantaginaceae	Europe	0.74	0.14	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Plantaginaceae	Europe	0.58	0.32	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Plantaginaceae	Europe	9.84	0.24	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Poaceae	Europe	1	0	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Poaceae	Europe	1	0	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Poaceae	Europe	1	0	Räsänen et al. 2007	https://doi.org/10.1016/j.revpalbo.2007.04.004
Poaceae	Europe	1	0	Hjelle 1998	https://doi.org/10.1007/BF01373926
Poaceae	Europe	1	0	Hjelle 1998	https://doi.org/10.1007/BF01373926
Poaceae	Europe	1	0	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Poaceae	Europe	1	0	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Poaceae	Europe	1	0	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Poaceae	Europe	1	0	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Poaceae	Europe	1	0	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Poaceae	Europe	1	0	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Poaceae	Europe	1	0	Niemeyer et al. 2015	https://doi.org/10.1177/0959683615596822
Poaceae	Europe	1	0	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Poaceae	Europe	1	0	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Populus	Europe	3.42	1.6	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Quercus	Europe	1.76	0.2	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Quercus	Europe	5.83	0	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Quercus	Europe	2.77	0.22	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Quercus	Europe	18.47	0.1032	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Quercus	Europe	2.56	0.39	Soepboer et al. 2007	https://doi.org/10.1177/0959683607073279
Quercus	Europe	1.1	0.35	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Quercus	Europe	1.7	0.03	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Ranunculaceae	Europe	0.7	0.004	Hjelle 1998	https://doi.org/10.1007/BF01373926
Ranunculaceae	Europe	0.08	0.02	Hjelle 1998	https://doi.org/10.1007/BF01373926
Ranunculaceae	Europe	3.91	0.72	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Ranunculaceae	Europe	2.31	0.35	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Ranunculaceae	Europe	0.59	0.09	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Rosaceae	Europe	0.14	0.005	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rosaceae	Europe	0.18	0.04	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rosaceae	Europe	2.46	0.85	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp

Rosaceae	Europe	2.45	0.4	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Rosaceae	Europe	0.97	0.12	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Rosaceae	Europe	0.29	0.12	Grindean et al. 2019	https://doi.org/10.1016/j.revpalbo.2019.02.007
Rubiaceae	Europe	0.42	0.01	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rubiaceae	Europe	0.13	0.03	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rubiaceae	Europe	3.95	0.59	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Rubiaceae	Europe	3.5	0.35	Mazier et al. 2008	https://doi.org/10.1007/s00334-008-0143-0
Rubiaceae	Europe	0.76	0.05	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Rumex	Europe	1.56	0.09	Nielsen 2004	https://doi.org/10.1111/j.1365-2699.2004.01080.x
Rumex	Europe	0.13	0.004	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rumex	Europe	0.04	0.02	Hjelle 1998	https://doi.org/10.1007/BF01373926
Rumex	Europe	4.74	0.83	Broström et al. 2004	https://doi.org/10.1191/0959683604hl713rp
Salix	Europe	1.19	0.12	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Salix	Europe	1.05	0.17	Bunting et al. 2005	https://doi.org/10.1191/0959683605hl821rr
Salix	Europe	0.03	0.03	Niemeyer et al. 2015	https://doi.org/10.1016/j.revpalbo.2015.06.008
Salix	Europe	0.09	0.03	von Stedingk et al. 2008	https://doi.org/10.1177/0959683607086769
Sambucus	Europe	1.3	0.12	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Tilia	Europe	1.36	0.26	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
Tilia	Europe	1.89	0.29	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Tilia	Europe	0.98	0.0263	Baker et al. 2016	https://doi.org/10.1177/0959683615596822
Tilia	Europe	0.45	0.02	Kunes et al. 2019	https://doi.org/10.1177/0959683619862026
Urtica	Europe	10.52	0.31	Abraham and Kozáková 2012	https://doi.org/10.1016/j.revpalbo.2012.04.004
wild herbs	Europe	0.07	0.07	Matthias et al. 2012	https://doi.org/10.1007/s00334-012-0373-z
Alnus	North America	2.7	0.12	Hopla 2017	https://eprints.soton.ac.uk/422162/
Artemisia	North America	1.35	0.24	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Asteraceae	North America	0.03	0.02	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Asteraceae	North America	1.36	0.36	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Asteraceae	North America	0.37	0.16	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Betula	North America	1.4	0.05	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Betula	North America	3.7	0.4	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Betula	North America	10.95	0.02	Hopla 2017	https://eprints.soton.ac.uk/422162/
Betula	North America	8.7	0.44	Hopla 2017	https://eprints.soton.ac.uk/422162/
Campanulaceae	North America	2.29	0.14	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Caryophyllaceae	North America	0.6	0.05	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Cornaceae	North America	1.72	0.14	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Cyperaceae	North America	0.95	0.05	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Cyperaceae	North America	1	0	Hopla 2017	https://eprints.soton.ac.uk/422162/
Equisetum	North America	0.09	0.02	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Ericales	North America	0.53	0	Hopla 2017	https://eprints.soton.ac.uk/422162/
Fabaceae	North America	0.02	0.02	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Juniperus	North America	20.67	1.54	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Lamiaceae	North America	0.72	0.08	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Moraceae	North America	1.1	0.55	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Orobanchaceae	North America	0.33	0.04	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Picea	North America	2.8	0	Hopla 2017	https://eprints.soton.ac.uk/422162/
Plantaginaceae	North America	5.96	0.31	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Poaceae	North America	1	0	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Poaceae	North America	1	0	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Poaceae	North America	1	0.07	Hopla 2017	https://eprints.soton.ac.uk/422162/
Poaceae	North America	1	0.18	Hopla 2017	https://eprints.soton.ac.uk/422162/
Populus	North America	1.23	17	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Populus	North America	0.11	0	Hopla 2017	https://eprints.soton.ac.uk/422162/

Quercus	North America	2.08	0.43	Commerford et al. 2013	https://doi.org/10.4236/ajps.2013.47A1001
Ranunculaceae	North America	1.95	0.1	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Rosaceae	North America	0.35	0.03	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Rumex	North America	3.53	0.3	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Rumex	North America	2.05	0.17	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Salix	North America	0.8	0	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003
Salix	North America	0.58	0	Hopla 2017	https://eprints.soton.ac.uk/422162/
Salix	North America	0.67	0.44	Hopla 2017	https://eprints.soton.ac.uk/422162/
Thalictrum	North America	4.65	0.3	Bunting et al. 2013	https://doi.org/10.1016/j.revpalbo.2012.11.003

Appendix B: RPP synthesis

		Asia				Europe				North America				Northern Hemisphere			
taxon	**level**	**RPP**	**SD**	**n**	**vg**	**RPP**	**SD**	**n**	**vg**	**RPP**	**SD**	**n**	**vg**	**RPP**	**SD**	**n**	**vg**
Acer	genus	0.087	0.062	1	0.019	0.23	0.043	3	0.056	-	-	-	0.056	0.152	0.037	3	0.038
Alnus	genus	0.85	1.53	1	0.021	8.492	0.215	4	0.02	2.7	0.12	1	0.021	6.538	0.154	6	0.02
Artemisia	genus	12.842	0.309	9	0.011	4.33	1.592	2	0.018	1.35	0.24	1	0.016	10.504	0.353	12	0.012
Betula	genus	7.492	0.127	6	0.016	4.94	0.443	6	0.024	6.188	0.149	4	0.038	6.361	0.362	18	0.024
Camellia	genus	0.583	0.019	1	0.023	-	-	-	-	-	-	-	-	0.583	0.019	1	0.023
Carpinus	genus	1.542	0.303	1	0.018	3.093	0.284	3	0.042	-	-	-	-	2.705	0.226	4	0.034
Castanea	genus	3.998	0.163	3	0.009	-	-	-	-	-	-	-	-	3.998	0.163	3	0.009
Castanopsis	genus	19.44	0.17	1	0.007	-	-	-	-	-	-	-	-	19.44	0.17	1	0.007
Corylus	genus	3.17	0.141	2	0.012	1.053	0.029	3	0.025	-	-	-	-	1.813	0.087	3	0.019
Cryptomeria	genus	-	-	-	0.015	-	-	-	-	-	-	-	-	-	-	1	0.015
Cyclobalanopsis	genus	2.411	0.136	1	0.011	-	-	-	-	-	-	-	-	2.411	0.136	1	0.011
Fraxinus	genus	1.05	0.178	2	0.02	1.83	0.303	3	0.022	-	-	-	-	1.616	0.195	5	0.021
Hippophae	genus	18.38	1.27	1	0.017	-	-	-	-	-	-	-	-	18.38	1.27	1	0.017
Humulus	genus	16.3	1	1	0.01	-	-	-	-	-	-	-	-	16.3	1	1	0.01
Ilex	genus	6.707	0.583	1	0.011	-	-	-	-	-	-	-	-	6.707	0.583	1	0.011
Juglans	genus	2.803	0.113	3	0.033	-	-	-	0.036	-	-	-	-	2.803	0.113	3	0.034
Larix	genus	2.8	0.181	4	0.12	5.725	1.165	2	0.126	-	-	-	0.126	3.002	0.596	6	0.121
Liquidambar	genus	2.255	0.117	1	0.031	-	-	-	-	-	-	-	-	2.255	0.117	1	0.031
Mallotus	genus	10.848	1.711	1	0.01	-	-	-	-	-	-	-	-	10.848	1.711	1	0.01
Malus	genus	0.087	0.037	1	0.028	-	-	-	-	-	-	-	-	0.087	0.037	1	0.028
Nitraria	genus	-	-	-	0.016	-	-	-	-	-	-	-	-	-	-	1	0.016
Picea	genus	16.4	0.601	2	0.09	1.645	0.153	4	0.056	2.8	0	1	0.056	3.04	0.154	7	0.09
Pinus	genus	16.475	0.691	10	0.048	10.86	0.798	4	0.038	-	-	-	0.028	14.58	0.476	16	0.043
Potentilla	genus	1.4	0.2	1	-	-	-	-	-	-	-	-	-	1.4	0.2	1	-
Quercus	genus	2.131	0.052	7	0.021	2.924	0.098	5	0.035	2.08	0.43	1	0.032	2.547	0.056	15	0.023
Rhododendron	genus	2.48	0.27	1	0.016	-	-	-	-	-	-	-	-	2.48	0.27	1	0.016
Salix	genus	0.23	0.11	1	0.022	0.39	0.058	3	0.028	0.683	0.147	3	0.019	0.57	0.081	6	0.024
Sanguisorba	genus	24.07	3.5	1	0.012	-	-	-	-	-	-	-	-	24.07	3.5	1	0.012
Selaginella	genus	-	-	-	0.041	-	-	-	-	-	-	-	-	-	-	1	0.041
Symplocos	genus	0.214	0.039	1	0.039	-	-	-	-	-	-	-	-	0.214	0.039	1	0.039
Syringa	genus	3.394	0.216	1	0.019	-	-	-	-	-	-	-	-	3.394	0.216	1	0.019
Thalictrum	genus	2.8	0.4	1	0.01	-	-	-	-	4.65	0.3	1	0.012	3.725	0.25	2	0.011
Tilia	genus	0.4	0.1	1	0.029	1.17	0.131	2	0.032	-	-	-	0.044	0.93	0.087	3	0.036
Ulmus	genus	2.025	0.312	3	0.022	-	-	-	0.032	-	-	-	-	2.025	0.312	3	0.022
Vitex	genus	-	-	-	0.016	-	-	-	-	-	-	-	-	-	-	1	0.016
Abies	genus	-	-	-	-	6.875	1.442	2	0.12	-	-	-	0.12	6.875	1.442	2	0.12
Aesculus	genus	-	-	-	-	-	-	-	0.029	-	-	-	-	-	-	1	0.029
Fagus	genus	-	-	-	-	2.35	0.107	3	0.057	-	-	-	0.057	2.35	0.107	3	0.057
Juniperus	genus	-	-	-	-	7.94	1.28	1	0.016	20.67	1.54	1	0.016	14.305	1.001	2	0.016
Populus	genus	-	-	-	-	3.42	1.6	1	0.025	0.67	8.5	2	0.026	1.587	5.692	3	0.026
Pterocarya	genus	-	-	-	-	-	-	-	0.042	-	-	-	-	-	-	1	0.042
Rumex	genus	-	-	-	-	0.577	0.031	3	0.018	2.79	0.172	2	0.014	1.817	0.089	4	0.016
Sambucus	genus	-	-	-	-	1.3	0.12	1	0.013	-	-	-	-	1.3	0.12	1	0.013
Urtica	genus	-	-	-	-	10.52	0.31	1	0.007	-	-	-	-	10.52	0.31	1	0.007
Equisetum	genus	-	-	-	-	-	-	-	-	0.09	0.02	1	0.021	0.09	0.02	1	0.021
Tsuga	genus	-	-	-	-	-	-	-	-	-	-	-	0.064	-	-	1	0.064
Altingiaceae	family	2.255	0.117	1	0.031	-	-	-	-	-	-	-	-	2.255	0.117	1	0.031

Amaranthaceae	family	13.156	0.643	8	0.013	4.28	0.27	1	0.019	-	-	-	0.011	12.17	0.573	9	0.014
Amaryllidaceae	family	1.64	0.4	1	0.013	-	-	-	-	-	-	-	-	1.64	0.4	1	0.013
Anacardiaceae	family	0.889	0.037	3	0.019	-	-	-	-	-	-	-	-	0.889	0.037	3	0.019
Apiaceae	family	-	-	-	0.011	2.127	0.41	3	0.042	-	-	-	-	2.127	0.41	3	0.027
Aquifoliaceae	family	6.707	0.583	1	0.011	-	-	-	-	-	-	-	-	6.707	0.583	1	0.011
Asteraceae	family	8.685	0.192	21	0.015	0.52	0.042	10	0.03	1.027	0.154	3	0.023	5.322	0.139	37	0.018
Betulaceae	family	5.442	0.592	10	0.016	5.195	0.145	21	0.028	5.033	0.202	3	0.033	5.394	0.181	38	0.025
Brassicaceae	family	2.145	0.135	2	0.012	0.07	0.04	1	0.028	-	-	-	-	1.453	0.091	3	0.019
Cannabaceae	family	16.3	1	1	0.01	-	-	-	-	-	-	-	-	16.3	1	1	0.01
Caryophyllaceae	family	13.043	0.628	4	0.024	-	-	-	-	0.6	0.05	1	0.04	10.608	0.504	5	0.03
Convolvulaceae	family	0.18	0.03	1	0.043	-	-	-	-	-	-	-	-	0.18	0.03	1	0.043
Cupressaceae	family	1.11	0.09	1	0.013	7.94	1.28	1	0.016	20.67	1.54	1	0.016	-	-	-	0.014
Cyperaceae	family	1.563	0.61	8	0.027	0.555	0.019	6	0.035	0.975	0.025	2	0.033	1.05	0.271	18	0.027
Elaeagnaceae	family	13.64	0.686	2	0.013	-	-	-	-	-	-	-	-	13.64	0.686	2	0.013
Eleagnaceae	family	18.38	1.27	1	0.017	-	-	-	-	-	-	-	-	18.38	1.27	1	0.017
Ephedraceae	family	22.87	0.76	1	0.014	-	-	-	-	-	-	-	-	22.87	0.76	1	0.014
Ericaceae	family	1.873	0.13	3	0.027	-	-	-	-	-	-	-	-	1.873	0.13	3	0.027
Euphorbiaceae	family	6.093	0.572	3	0.009	-	-	-	-	-	-	-	-	6.093	0.572	3	0.009
Fabaceae	family	0.209	0.051	2	0.016	0.4	0.07	1	0.021	0.02	0.02	1	0.021	0.244	0.038	5	0.017
Fagaceae	family	2.93	0.053	12	0.017	3.027	0.09	10	0.052	2.08	0.43	1	0.038	3.449	0.047	25	0.025
Gentianaceae	family	-	-	-	0.02	-	-	-	-	-	-	-	-	-	-	1	0.02
Iridaceae	family	-	-	-	0.012	-	-	-	-	-	-	-	-	-	-	1	0.012
Juglandaceae	family	2.576	0.087	4	0.033	-	-	-	0.039	-	-	-	-	-	-	-	0.035
Lamiaceae	family	1.457	0.16	3	0.015	-	-	-	-	0.72	0.08	1	0.031	-	-	-	0.018
Liliaceae	family	1.97	0.207	2	0.014	-	-	-	-	-	-	-	-	1.97	0.207	2	0.014
Malvaceae	family	0.4	0.1	1	0.029	1.17	0.131	2	0.032	-	-	-	0.044	0.93	0.087	3	0.036
Moraceae	family	6.52	0.08	1	0.008	-	-	-	-	1.1	0.55	1	0.016	3.81	0.278	2	0.012
Nitrariaceae	family	-	-	-	0.016	-	-	-	-	-	-	-	-	-	-	1	0.016
Oleaceae	family	1.831	0.139	3	0.019	1.83	0.303	3	0.022	-	-	-	-	1.912	0.167	6	0.02
Papilionaceae	family	2.66	0.05	1	0.007	-	-	-	-	-	-	-	-	2.66	0.05	1	0.007
Pinaceae	family	12.073	0.437	18	0.072	6.091	0.354	14	0.061	2.8	0	1	0.072	-	-	-	0.068
Plantaginaceae	family	-	-	-	0.013	2.486	0.107	8	0.028	5.96	0.31	1	0.019	2.872	0.101	9	0.022
Poaceae	family	1	0.012	16	0.023	1	0	14	0.036	-	-	-	0.031	1	0.008	34	0.024
Polygonaceae	family	26.35	1.85	1	0.024	0.577	0.031	3	0.018	2.79	0.172	2	0.014	2.402	0.181	5	0.02
Ranunculaceae	family	5.33	1.34	2	0.01	1.2	0.12	3	0.014	3.3	0.158	2	0.013	2.416	0.136	7	0.012
Rosaceae	family	0.824	0.057	4	0.015	0.973	0.109	4	0.012	0.35	0.03	1	0.014	0.921	0.089	11	0.014
Rubiaceae	family	1.26	0.18	2	0.015	1.56	0.118	3	0.019	-	-	-	-	1.44	0.101	5	0.015
Salicaceae	family	0.23	0.11	1	0.022	0.777	0.07	3	0.027	0.683	0.147	3	0.022	0.661	1.89	9	0.025
Sapindaceae	family	0.087	0.062	1	0.019	0.23	0.043	3	0.043	-	-	-	0.056	-	-	-	0.035
Selaginellaceae	family	-	-	-	0.041	-	-	-	-	-	-	-	-	-	-	1	0.041
Solanaceae	family	-	-	-	0.027	-	-	-	-	-	-	-	-	-	-	1	0.027
Symplocaceae	family	0.214	0.039	1	0.039	-	-	-	-	-	-	-	-	0.214	0.039	1	0.039
Tamaricaceae	family	1.5	0.13	1	-	-	-	-	-	-	-	-	-	1.5	0.13	1	-
Theaceae	family	0.583	0.019	1	0.024	-	-	-	-	-	-	-	-	0.583	0.019	2	0.024
Thymelaceae	family	33.05	3.78	1	0.009	-	-	-	-	-	-	-	-	33.05	3.78	1	0.009
Ulmaceae	family	1.298	0.173	2	0.022	-	-	-	0.032	-	-	-	-	1.298	0.173	2	0.022
Urticaceae	family	-	-	-	-	10.52	0.31	1	0.007	-	-	-	-	10.52	0.31	1	0.007
Viburnaceae	family	-	-	-	-	1.3	0.12	1	0.013	-	-	-	-	1.3	0.12	1	0.013
Campanulaceae	family	-	-	-	-	-	-	-	-	2.29	0.14	1	0.022	2.29	0.14	1	0.022
Cornaceae	family	-	-	-	-	-	-	-	-	1.72	0.14	1	0.044	1.72	0.14	1	0.044
Equisetaceae	family	-	-	-	-	-	-	-	-	0.09	0.02	1	0.021	0.09	0.02	1	0.021
Onagraceae	family	-	-	-	-	-	-	-	-	-	-	-	0.098	-	-	1	0.098

Orobanchaceae	family	-	-	-	-	-	-	-	-	0.33	0.04	1	0.038	0.33	0.04	1	0.038
Apiales	order	-	-	-	0.011	2.127	0.41	3	0.042	-	-	-	-	2.127	0.41	3	0.027
Aquifoliales	order	6.707	0.583	1	0.011	-	-	-	-	-	-	-	-	6.707	0.583	1	0.011
Asparagales	order	1.64	0.4	1	0.012	-	-	-	-	-	-	-	-	1.64	0.4	2	0.012
Asterales	order	8.685	0.192	21	0.015	0.52	0.042	10	0.03	1.027	0.154	3	0.023	5.242	0.136	38	0.018
Brassicales	order	2.145	0.135	2	0.012	0.07	0.04	1	0.028	-	-	-	-	1.453	0.091	3	0.019
Caryophyllales	order	13.408	0.39	16	0.017	1.99	0.095	3	0.018	2.06	0.116	3	0.026	9.65	0.263	24	0.019
Coniferales	order	29.4	0.87	1	0.071	-	-	-	0.056	-	-	-	0.064	-	-	-	0.071
Ephedrales	order	22.87	0.76	1	0.014	-	-	-	-	-	-	-	-	22.87	0.76	1	0.014
Ericales	order	1.241	0.095	3	0.028	0.436	0.015	7	0.032	0.53	0	1	0.038	-	-	-	0.028
Fabales	order	0.4	0.036	3	0.015	0.4	0.07	1	0.021	0.02	0.02	1	0.021	0.333	0.032	6	0.016
Fagales	order	4.063	0.206	30	0.02	4.786	0.096	33	0.036	4.295	0.186	4	0.036	-	-	-	0.027
Gentianales	order	1.26	0.18	2	0.017	1.56	0.118	3	0.019	-	-	-	-	-	-	-	0.017
Lamiales	order	1.567	0.145	4	0.016	2.673	0.117	13	0.026	2.337	0.108	3	0.029	-	-	-	0.022
Liliales	order	1.97	0.207	2	0.014	-	-	-	-	-	-	-	-	1.97	0.207	2	0.014
Malphighiales	order	2.553	0.056	3	0.015	0.777	0.07	3	0.027	0.683	0.147	3	0.022	1.053	1.553	11	0.022
Malphigiales	order	10.848	1.711	1	0.01	-	-	-	-	-	-	-	-	10.848	1.711	1	0.01
Malvales	order	16.725	1.891	2	0.022	1.17	0.131	2	0.032	-	-	-	0.044	1.17	0.098	4	0.031
Pinales	order	10.502	0.435	18	0.069	6.214	0.342	15	0.056	11.735	0.77	2	0.062	8.893	0.256	37	0.063
Poales	order	1.188	0.204	24	0.025	0.555	0.019	6	0.036	-	-	-	0.031	1.017	0.094	52	0.026
Ranunculales	order	5.33	1.34	2	0.01	1.2	0.12	3	0.014	3.3	0.158	2	0.013	2.416	0.136	7	0.012
Rosales	order	6.761	0.197	11	0.017	1.27	0.191	5	0.015	0.725	0.275	2	0.015	4.642	0.122	20	0.016
Sapindales	order	0.328	0.04	3	0.019	0.23	0.043	3	0.043	-	-	-	0.056	-	-	-	0.028
Saxifragales	order	2.255	0.117	1	0.031	-	-	-	-	-	-	-	-	2.255	0.117	1	0.031
Selaginellales	order	-	-	-	0.041	-	-	-	-	-	-	-	-	-	-	1	0.041
Solanales	order	0.18	0.03	1	0.035	-	-	-	-	-	-	-	-	0.18	0.03	2	0.035
Spaindales	order	-	-	-	0.016	-	-	-	-	-	-	-	-	-	-	1	0.016
Cerealia	order	-	-	-	-	2.311	0.422	4	0.069	-	-	-	-	2.311	0.422	4	0.069
Dipsacales	order	-	-	-	-	1.3	0.12	1	0.013	-	-	-	-	1.3	0.12	1	0.013
wild herbs	order	-	-	-	-	0.07	0.07	1	0.034	-	-	-	-	0.07	0.07	1	0.034
Cornales	order	-	-	-	-	-	-	-	-	1.72	0.14	1	0.044	1.72	0.14	1	0.044
Equisetales	order	-	-	-	-	-	-	-	-	0.09	0.02	1	0.021	0.09	0.02	1	0.021
Myrtales	order	-	-	-	-	-	-	-	-	-	-	-	0.098	-	-	1	0.098
Myrtales	order	-	-	-	-	-	-	-	-	-	-	-	0.098	-	-	1	0.098

Author contributions. UH conceptualized the data set production. CL curated the pollen dataset supervised by UH. CL revised age models supervised by UH. CL, PE and LS collected metadata for pollen records supervised by. PE set up, improved and tested code to run the REVEALS model and run the initial Reveals reconstructions supervised by UH. LS, TL, RH, and UH developed the optimization methodology. LS wrote optimization code, curated remote sensing data and executed optimization, final reconstructions and validations. TL, RH and UH provided supervision for LS. LS prepared the original draft supervised by UH. All authors reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. We thank Thomas Böhmer for support with dataset curation and harmonization. The project was supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie through the German Climate Modeling Initiative PALMOD (grant no. 01LP1510C to UH), the European Union (ERC, GlacialLegacy grant no. 772852 to UH), and the China Scholarship Council (grant no. 201908130165 to CL). Data were partly obtained from the Neotoma Paleoecology Database (http://www.neotomadb.org) and its constituent databases (European Pollen Database, QUAVIDA data base for Australasia, Latin American Pollen Database, African Pollen Database and the North American Pollen database). The work of data contributors, data stewards, and the Neotoma community is gratefully acknowledged.

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