LegacyVegetation: Northern Hemisphere reconstruction of past plant cover and total tree 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 tree cover for each original pollen sample. Additional metadata includes modeled ages, age model sources, basin locations, types, and sizes.

The improvements in tree cover reconstructions with the REVEALS reconstruction using continental RPP values range from 22% (Asia) to 67% (Europe) relative to the mean absolute error (MAE) of the pollen-based tree cover. The dataset can be used as a grid with binned and aggregated samples (adjustable script provided on Zenodo; https://doi.org/10.5281/zenodo.13902976) or as individual time series if the record's basin size exceeds 50 ha.

This alternative quantitative reconstruction of vegetation cover is beneficial for the investigation of past vegetation dynamics and modern model validation when varying spatial and temporal resolutions may be required. 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 new REVEALS dataset 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 thorough mechanistic understanding of vegetation dynamics and their interactions with climate is essential. This requires validating and testing data from coupled climate-vegetation models, which in turn depends on the availability of extensive vegetation data from periods spanning climatic transitions. (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., 2009; 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; ?; Herzschuh et al., 2022)~~(Li et al., 2022a; Herzschuh et al., 2022). This taxonomic harmonization trades off the 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, titled the Fagerlind effect (Prentice and Webb III, 1986; Fagerlind, 1952). 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 later included into 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 estimates regional vegetation cover from pollen counts. The model has been applied in several regional-scale studies (Nielsen et al., 2012; Mazier et al., 2015; Hellman et al., 2008a) and multiple validations have demonstrated its ability to approximate actual vegetation (Sugita et al., 2010; Hellman et al., 2008a; Soepboer et al., 2010; Mazier et al., 2012), even though the model's performance heavily relies on accurate taxon-specific parameters. While Li et al. (2017), Wieczorek and Herzschuh (2020), and Githumbi et al. (2022) provide comprehensive compilations of RPP and fall speed values for taxa of China, the Northern Hemisphere, and Europe the Northern Hemisphere respectively, 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, tree 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 tree cover, reconstructions of tree cover in modern time slices may even be validated (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 tree 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, and the North American Pollen database (?Giesecke et al., 2014; Whitmore et al., 2005; Williams et al., 201 (Fyfe et al., 2009; Giesecke et al., 2014; Williams et al., 2018). An overview of Neotoma records included in LegacyPollen 2.0 and this reconstruction can be found in S1.

For the REVEALS reconstruction only lake and peat records in the Northern Hemisphere were used (n = 2752) Analogous to the preceding LegacyPollen 1.0 dataset (Herzschuh et al., 2022), the data synthesis involved revising and standardizing age modeling and taxonomic harmonization for consistency of records. Reconstruction chronologies may, therefore, differ slightly from previous reconstructions due to this revised age modeling. Spatial data coverage of records in the reconstruction is dense in Europe (1287 records) and North America (1040) and sparsest in Asia (446) (see Fig. 1). The records' sample density decreases with age (see Fig. 2). Only samples dated to 14 ka BP or younger were used to ensure that the climatic conditions of recorded vegetation were similar to the modern climate Shakun et al. (2012); Mottl et al. (2021); ? (Shakun et al., 2012; Mottl et al., 2021; Li et al., 2024c).

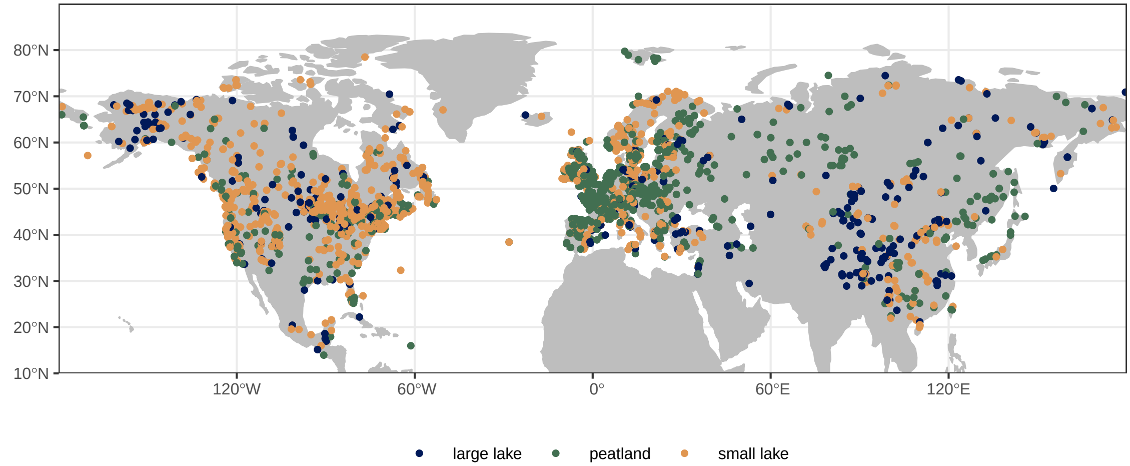

Figure 1. Pollen record locations in the LegacyVegetation dataset. Colors indicate record type (large lake $\geq$ 50 ha). Record density is highest in Europe and Eastern North America, and lowest in Northern and Central Asia.

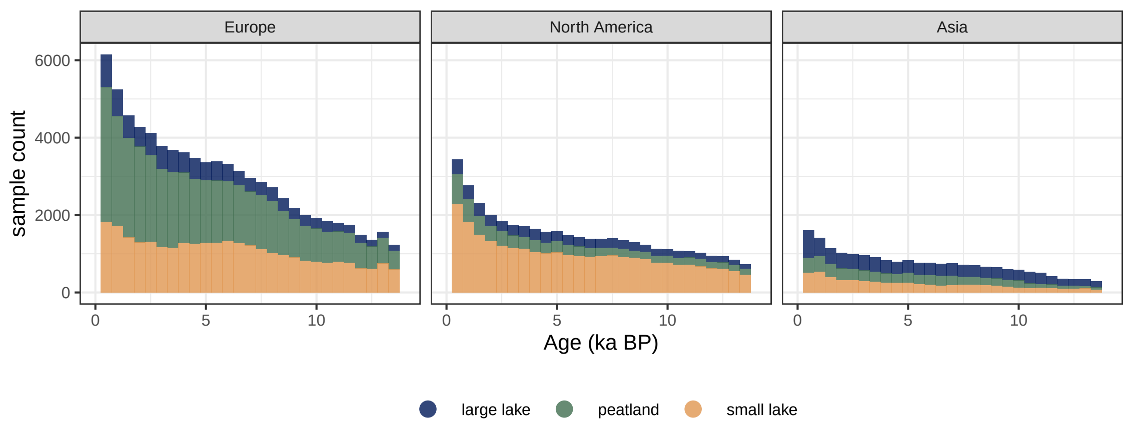

Figure 2. Temporal coverage of records in the LegacyVegetation dataset per continent. Bins are 500 years wide. Sample count decreases with age and Europe has the most samples overall.

2.2 Implementing REVEALS

The REVEALS model 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 lake 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).

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

The REVEALS model follows a set of assumptions. Firstly, neither directionality nor pollen transport through agents other than wind are considered in the model. The maximum spatial extent for this pollen transport (Z_{max}, see Table 2) has to be set to define the region in which most of the pollen originates. This value will always be an assumption and has only been tested empirically by Hellman et al. (2008b). 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 alone tend to deviate from those of large lakes due to the violation of the aforementioned assumption (Trondman et al., 2016). Using small peatland records for reconstructions is, therefore, appropriate when spatially averaging multiple sites. Following Trondman et al. (2015), we ~~do so~~ average multiple sites by using both large and small peatlands. We use REVEALSinR from the DISQOVER package in R to implement REVEALS (Theuerkauf et al., 2016, Version 0.9.13, https://github.com/MartinTheuerkauf/disqover/blob/main/disqover). It mainly differs from the original program by Sugita (2007) in the process of error calculation. REVEALSinR includes repeated model runs with random error added to RPP values and pollen counts (see Table 2 for the number of variations). The resulting distribution of REVEALS results allows for an estimation of the standard deviation of vegetation cover per taxon. ~~The~~ These error estimates are included in our dataset as the standard deviations as well as the 10th and 90th percentile estimates for each taxon. However, the program by Sugita (2007) ~~, however,~~ derives error estimates with a hybrid method from a variance-covariance matrix of PPE and Monte Carlo simulations. For further details on the REVEALS model see the original publication Sugita (2007) and for previous REVEALS applications on continental scales see e.g Li et al. (2017), Githumbi et al. (2022), Serge et al. (2023), and Dawson et al. (2024).

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

While the error estimates give insights into how certain the model is, estimates can still be wrong depending on the quality of RPP values provided.

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 for study selection and calculation of synthesis values follow Wieczorek and Herzschuh (2020) as well as Githumbi et al. (2022). We expanded the synthesis calculation of RPP to different taxonomic levels (genus, family, and order) to account for the taxonomic harmonization in the pollen dataset. An overview of original values and synthesized values can be found in Appendix A and B respectively. The amount of available RPP values in Asia (59) and Europe (69) is higher than in previous RPP synthesis due to the inclusion of multiple taxonomic levels (Li et al., 2018; Githumbi et al., 2022).

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 in order to maximize the number of taxa used in the reconstruction. Continental RPP values are available for the majority of pollen counts in all three continents (see Fig. 3). The fraction of pollen ~~counts~~ sums 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). Missing basin areas for lakes and peatlands are set to a standard value which can be found in Table 2 together with several constant parameters set in REVEALSinR. For the standard value of missing lake areas, we build on the standard value of 50 ha used by Dawson et al. (2024). However, we reduce it slightly as not to have those lakes count as large lakes (see Reconstruction of tree cover and validation). Lastly, 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 now set to 500 unless m falls below that maximum value for $m = basin\,radius/10$ for basins with a radius of at least 1000 m and $m = basin\,radius/2$ for basins with a radius smaller than 1000 m. This adjustment prevented unnecessarily small steps for large lakes while maintaining robust and reliable results.

2.3 Reconstruction of tree cover and validation

Tree 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 60° N. The mean reconstructed compositional coverages from the REVEALS results were used for the tree cover reconstructions. REVEALS results were then rasterized to also include records from smaller basins in a temporal and spatial aggregation. Reconstructed time series were averaged in 500 year bins and then rasterized and averaged in grids of differing spatial resolution. A grid cell was classified as having a valid reconstruction when

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 (Z_{max})	1000 km
number of RPP and pollen count variations (n)	2000
peatland basin area (for missing sizes)	31.41 ha
lake basin area (for missing sizes)	49 ha
function to randomize pollen counts	rmultinom_reveals

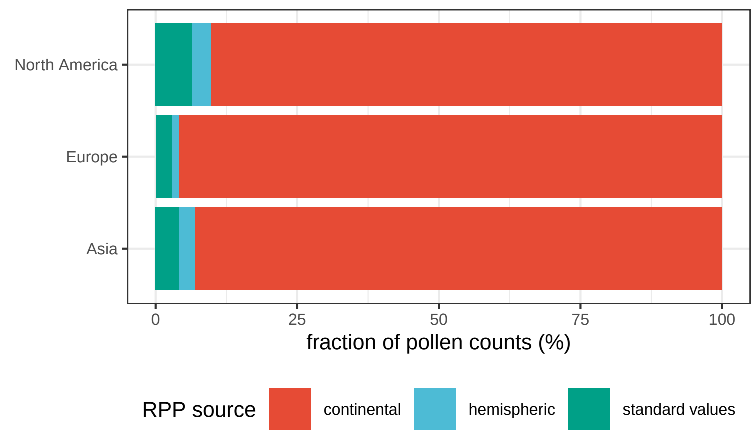

Figure 3. Percentage of the total pollen counts for which either continental, hemispheric, or "standard" RPP values were used. The standard value (1+-0,5) is used when no RPP value is available for a specific taxon.

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).

This method of temporal and spatial averaging differs from several previous REVEALS applications. Pollen counts are often summed in temporal bins prior to running REVEALS to increase pollen counts and reduce uncertainty (Trondman et al., 2015; Githumbi et al., 2022; Serge et al., 2023; Dawson et al., 2024). However, temporally averaging after the REVEALs application, as implemented by us, increases the flexibility of the dataset's spatial and temporal resolution with the trade-off of potentially increased uncertainty. Rasterization has previously been ~~perfomred~~ performed by using a weighted average taking into account the basin size of the original record (Trondman et al., 2015; Githumbi et al., 2022; Serge et al., 2023). However, the most recent REVEALS-based North American vegetation reconstruction uses the same arithmetic mean as described above ~~(?)~~ (Dawson et al., 2024). When comparing our method of temporal and spatial aggregation to that used by previous European reconstructions (e.g. Serge et al., 2023), we also found no significant differences in the validation of reconstructed tree cover (see S6).

For validation, the reconstructed tree cover of ~~the past~~ all samples younger than 100 years BP was rasterized and compared to modern remote sensing forest cover. Only valid grid cells as defined above were used for validation. Average forest 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 (Supplementary Materials S5) 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. Reconstructed tree cover was validated for each grid cell and mean absolute error (MAE $= \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i|$) and correlation coefficients were 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 (S4).

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

$$unvegetated\, classes = \{190, 200, 201, 202\} \quad (2)$$

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

$$corrected\, tree\, cover = reconstructed\, tree\, cover \times (1 - unvegetated) \quad (4)$$

Additionally, we compare our REVEALS reconstruction to the most recently published REVEALS reconstruction in Europe by Serge et al. (2023, version: RPPs.st1). We average our reconstruction in the same grid and temporal bins as used by Serge et al. to compare the reconstructed tree cover between both reconstructions. To get the total tree cover, we sum evergreen and summergreen tree cover values in Serge et al.'s dataset, while excluding broadleaved summergreen temperate warm shrubs (BSTWS) and broadleaved evergreen xeric shrubs (BEXS). We validate the previous reconstruction and our reconstruction in the most recent time slice available in Serge et al.'s reconstruction (-65 to 100 BP, https://doi.org/10.48579/PRO/J5GZUO) with the remote sensing forest cover and compare validations. Unfortunately, direct validation could only be performed with the most recent time slice available online, rather than the historical time slice used in the validation by Serge et al., which limits the ability to reproduce their validation results exactly. We do not apply any openness correction here as we do not have comparable 80% pollen source areas available for the records used in Serge et al. (2023). The reconstruction by Serge et al. differs in the temporal as well as spatial aggregation routine, as described above. Definition of arboreal taxa varies, a different RPP-value set was used, and the amount of total records included is higher than in our reconstruction (~~Serge et al.~~Serge et al. (2023): 1607, LegacyVegetation: 1287).

3 Data summary

3.1 Dataset description

The published dataset includes vegetation reconstructions for individual records in Asia, Europe, and North America up until 14 ka BP. The reconstructed coverage values include mean, median, standard deviation, and 10% and 90% quantile values for each taxon. Mean values and standard deviations are given for tree cover. For each sample its validity as a site is given ~~. Only~~ as only reconstructions from large lakes are valid independently. To include all other records a spatial and temporal average is necessary (rasterization, https://doi.org/10.5281/zenodo.12800291).

REVEALS was used to reconstruct quantitative vegetation cover. Here we illustrate a comparison between 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~~Ericales in Europe, decreases of *Betula* in 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-specific biases (see Fig. 4).

Using the compositional data available from the original pollen data and the REVEALS run, we reconstructed tree cover for all sites and samples and rasterized the result with different spatial resolutions. The temporal trend in Northern Hemisphere tree cover is the same for both pollen and REVEALS data. Tree cover increases from 14 ka BP until roughly 6 ka BP and decreases again towards the present (see Fig. 5). REVEALS reconstructed tree cover is generally lower than ~~tree cover from original pollen compositions~~the percent tree pollen in the original samples. However, the difference between pollen and REVEALS tree cover is smaller in North America compared to Europe and Asia. On average tree 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

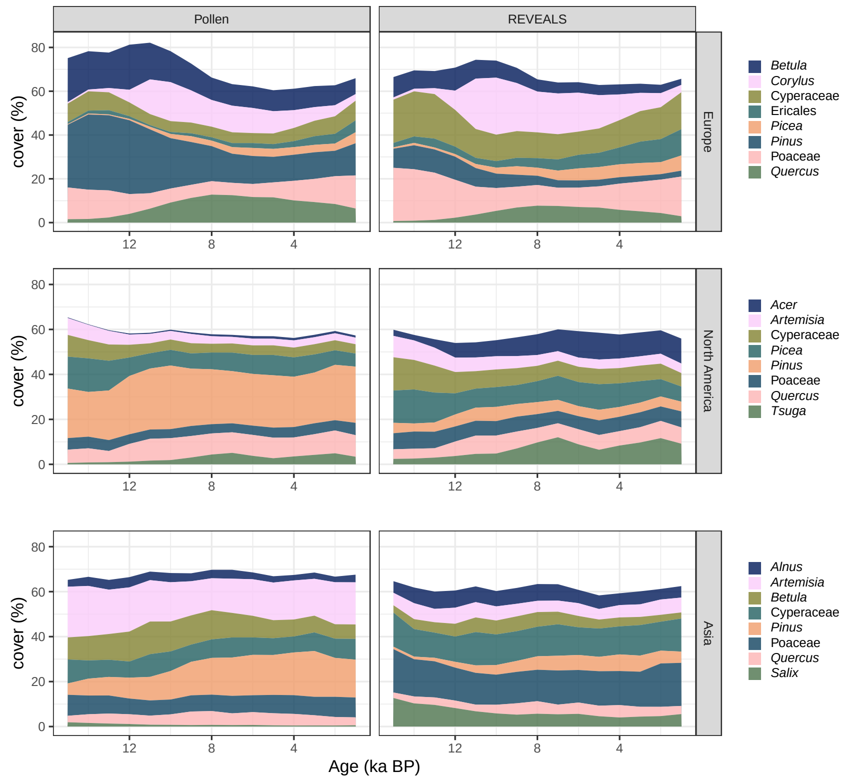

Figure 4. Average continental taxonomic coverages per reconstruction for the 8 most common taxa per continent. Differences are especially evident for *Pinus*, *Artemisia*, and *Betula*, which all have decreased coverages after the application of REVEALS, as well as Poaceae and ~~Cyperaceae~~ Ericales with increased coverages.

positive, whereas tree cover in Europe reached its maximum around 6 ka BP and has been decreasing since.

Tree cover is generally highest in Eastern North America. This is also where data coverage is best in North America (see Fig. 6). The density of valid grid cells is very high in Europe. Data coverage in Asia is sparse, but valid grid cells indicate higher tree cover on the Southeastern coast and in the boreal biome than in central Asia. Rather open areas exist ~~at~~ on the Tibetan Plateau and at very high latitudes. ~~The tree cover derived from the REVEALS reconstruction is generally lower than tree pollen percentages. However, the difference between pollen and REVEALS tree cover is smaller in North America than in Europe and Asia.~~

3.2 Validation with gridded data sets

Remote sensing forest cover within grid cells was used to validate the modern, reconstructed tree cover from the original pollen data and the REVEALS estimates 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 (S4).

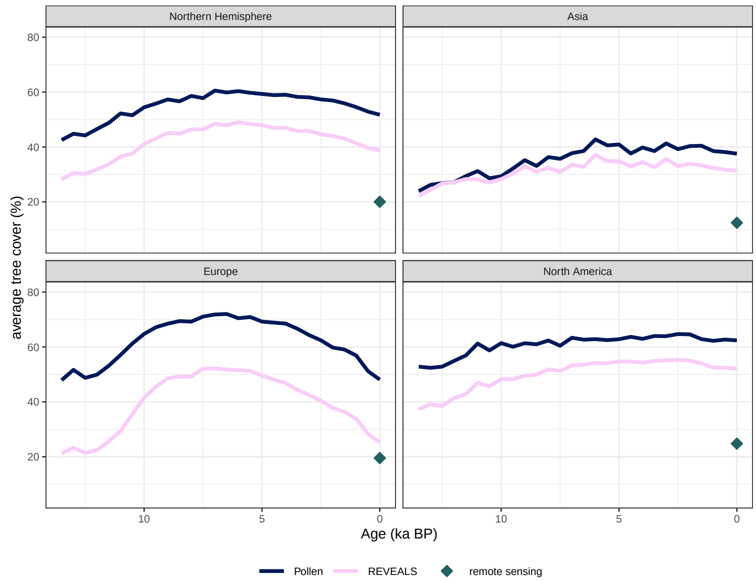

Figure 5. Northern Hemisphere and continental mean tree pollen percentage and mean REVEALS tree cover for 2°x2° grid cells through the Holocene. (Northern Hemisphere and continental averages from different grid cell resolutions are available in S3: Reconstruction results for different spatial resolutions). Remotely sensed average forest cover for the grid cells with valid pollen coverage (at least one large lake or multiple other basins present in the time slice) is indicated with the diamond. Temporal trends are the same, but absolute tree cover is reduced in the REVEALS reconstructions compared to the original pollen data. Both pollen percentages and REVEALS estimates still overestimate tree cover.

Tree ~~cover from original pollen percentages is~~ pollen percentages from original samples are predominantly higher than remote sensing forest cover with a mean absolute error (MAE) of 31.67% in the Northern Hemisphere (see Fig. 7). As reconstructed tree cover is much lower for the REVEALS reconstruction (see Fig.5), the MAE value is reduced significantly to 20.03% (see Fig. 7).

~~Continental~~ Average continental mean absolute errors (MAE) in tree cover from original pollen data range from 24.7% (Asia) to 35.87% tree cover (North America, see Fig. 7b). All continental MAE values are lower for the REVEALS reconstruction and range from 9.67% (Europe) to 26.43% (North America). The improvement is largest in Europe (67% relative to the initial MAE of the pollen-based ~~reconstruction~~tree percentage, see Fig. 7 and 8) and smallest in Asia (22%). REVEALS reconstructed tree cover also increases correlation coefficients with the exception of Asia. The REVEALS run, therefore, produced reconstructed tree cover that corresponds better remote sensing forest cover. Nevertheless, tree cover still tends to be overestimated. Spatial patterns are present for the errors of both tree cover reconstructions (see Fig. 9). In Europe the REVEALS reconstruction manages to reduce errors extensively. In Eastern and coastal Northwestern North America, the REVEALS reconstruction still

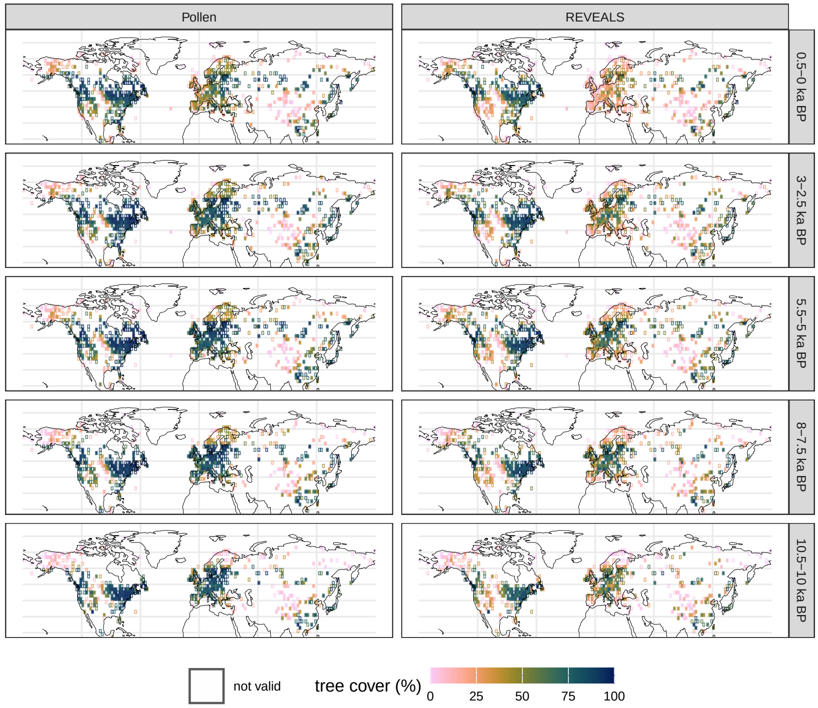

Figure 6. Total tree pollen percentages and REVEALS reconstructed tree cover in 2x2° grid cells for 5 example time slices (reconstructions with different grid cell sizes are available in the in S3: Reconstruction results for different spatial resolutions). Valid cells are filled and include reconstructions from at least one large lake ($\geq$ 50 ha) or several smaller basins. Tree cover in Eastern North America is higher than in Europe and Asia. REVEALS reconstructed tree cover is generally lower than tree pollen percentages.

tends to overestimate tree cover.

The comparison between our reconstruction and tree cover reconstructed in Serge et al. (2023) shows that LegacyVegetation (this publication) tends to have a lower tree cover independent of sample age ~~.~~(Fig. 10 a). Serge et al. tend to overestimate forest cover even more than LegacyVegetation which leads to a much lower mean absolute error in LegacyVegetation compared to Serge et al. (Fig. 10 b). The MAE for LegacyVegetation is slightly higher than presented in Fig. 7 due to the difference in spatial resolution and the lack of openness correction.

4 Discussion

4.1 Continental patterns in reconstruction validity

Our reconstructed quantitative vegetation cover datasets using REVEALS provide reconstructions of taxonomic compositions as well as tree cover in Europe, Asia, and North America and extend to 14 ka BP. The reconstructions made use of taxon-

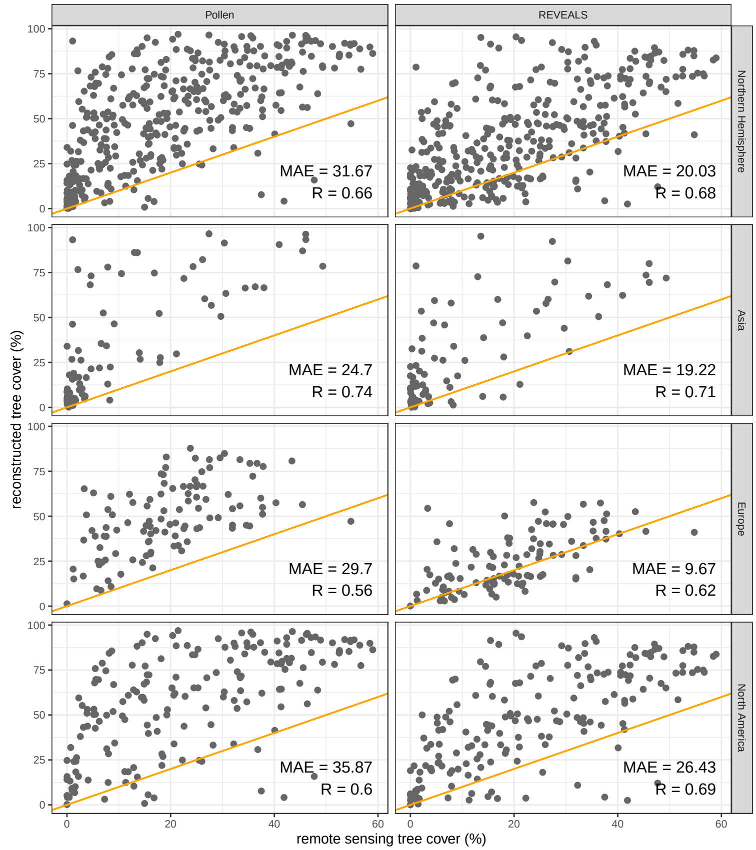

Figure 7. Remote sensing tree cover (LANDSAT) and modern tree cover from tree pollen and REVEALS estimates (< 100 years BP) in 2x2° grid cells with mean absolute errors (MAE, see Methods section) and correlation coefficient (R) per group. Reconstructed tree cover from the original pollen data tends to overestimate observed (remote sensing) forest cover. Tree pollen percentages tend to overestimate observed tree cover from remote sensing data more than REVEALS estimated tree cover. The correlation between REVEALS estimates of tree cover and observed data is generally better, especially for Europe. Validations with different grid cell sizes are available in the supplement (S4).

specific parameters and were, thus, able to correct some of the compositional biases present in pollen compositions. Notably, the error in modern reconstructed tree cover was reduced compared to pollen-based reconstructions on all continents which shows that improvements in tree cover reconstructions from REVEALS applications are considerable.

However, continental differences are evident in the quality of tree cover reconstruction, with Europe showing a significantly larger reduction in errors compared to other regions. North America and Asia exhibit larger reconstruction errors in the REVEALS estimates, though these are still lower than those derived from tree pollen percentages. Notably, regions such as the Great Lakes, the Labrador Peninsula, and the Pacific Northwest display particularly high errors in tree cover reconstruction. Asia, characterized by sparser coverage, presents fewer large errors increasing the overall continental reconstruction error. This

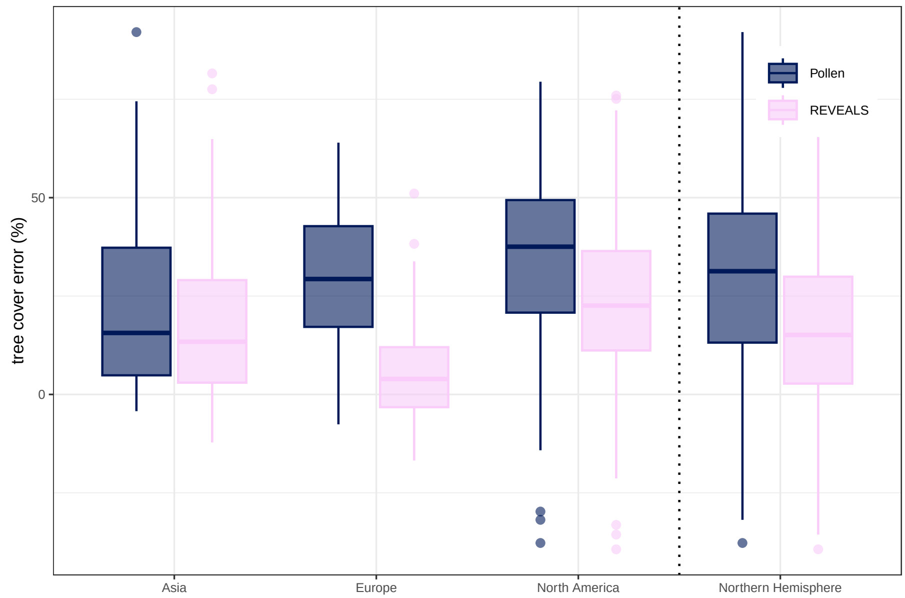

Figure 8. Tree pollen percentage and tree cover reconstruction error per continent for a gridded 2x2° reconstruction. Mean errors decreased with the REVEALS reconstruction for all continents but are still generally > 0 (overestimation of tree cover). Lowest errors are present in Europe.

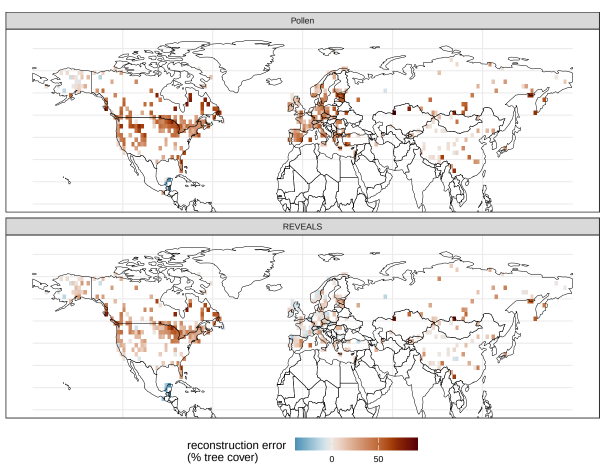

Figure 9. Map of the reconstruction error (in % tree cover) for tree cover from pollen counts and REVEALS estimates. Remaining errors with the overall better REVEALS reconstructions are especially high in North America (Northern West Coast, Labrador Peninsula).

highlights the need for improved vegetation reconstruction, especially in North America and Asia. The reason for this reduced performance could lie in a lack of RPP studies, especially in North America, or in a significantly higher regional variability

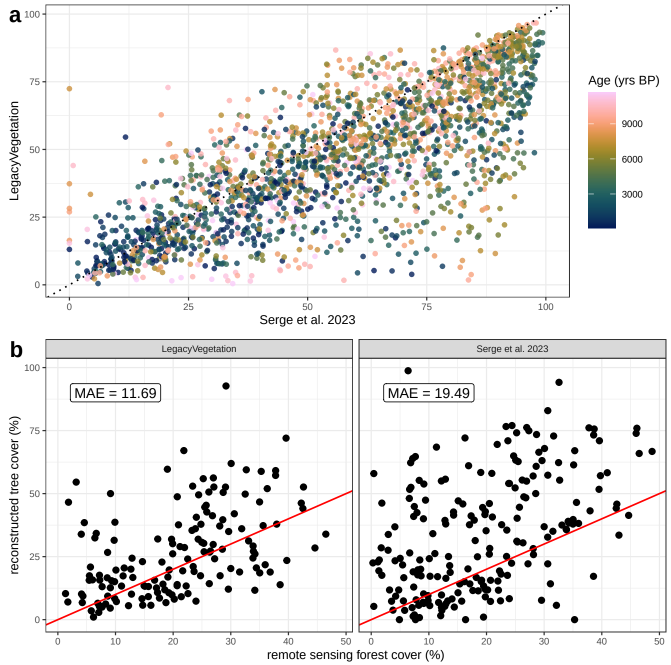

Figure 10. (a) Comparison between LegacyVegetation (this publication) and the tree cover from Serge et al. (2023) and (b) validations with modern, remote-sensing forest cover for both data sets.

of RPP values compared to Europe. While differences in validation outcomes across varying spatial resolutions are marginal (see S4), some variability is observed when different grids are employed, highlighting spatial heterogeneity in reconstruction success. Despite these caveats, overall trends in tree cover appear consistent, with acceptable correlation coefficients, though absolute values in certain regions remain challenging to interpret with confidence as tree cover continues to be overestimated in all continents. As a result, arboreal taxa might still be overrepresented in the reconstruction because of inaccurate or missing RPP values. Very few grid cells, predominantly in central Europe, slightly underestimate forest cover.

A specific comparison with the previous European REVEALS reconstruction by Serge et al. (2023) reveals that our reconstruction generally shows lower forest cover across Europe and demonstrates a much lower MAE, indicating improved accuracy. This is notable given that Serge et al. utilized a larger number of records in their study. One potential explanation for these differences could lie in the variations in RPP values and the selection of arboreal taxa used in the reconstruction, as we employ an arboreal tree threshold and include more taxa in our REVEALS reconstruction.

In general, the tree cover trends in our reconstruction results are similar to available large-scale pollen-based vegetation reconstructions. Increases in tree 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 tree cover in China with low tree cover in the North China plain and the Tibetan Plateau and a higher tree cover along the east coast and the south agree with previous reconstructions as well (Li et al., 2023, 2022b, 2024a). Results for European tree cover trends also roughly correspond with previous REVEALS applications and show an increase of tree 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). Still, this is the first effort to apply REVEALS across the Northern Hemisphere and reconstruct vegetation with a gridded, large-scale validation using remote sensing data, and a clear improvement of reconstruction success compared to the most recent European reconstruction.

4.2 Data use and methodological limitations

To ensure proper dataset utilization and obtain reliable analytical results, several key considerations must be followed. The reliability of individual time series data varies based on the size of the lakes from which samples were taken. Only data from large lakes (≥ 50 ha) are considered reliable for site-specific analyses, and these are clearly marked with validity flags in the dataset. When incorporating records from smaller lakes or other sources, rasterization is necessary (https://zenodo.org/records/12800291). Although our rasterization method is more flexible than previous efforts, the temporal and spatial aggregation used may reduce its reliability, due to smaller total pollen counts used in REVEALS runs and the use of an arithmetic as opposed to a weighted spatial mean. We do however find that reconstructions differences between these methods are marginal (S6).

The reliability of reconstructions also varies among different taxa due to the quality of RPP values, which is documented in detail in a supplementary file outlining the sources of RPP values (see Section "Code and Data Availability"). Reconstructions based on 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 considered when interpreting results. The use of continental RPP values could also make our reconstruction more reliable at larger spatial scales as opposed to local reconstructions. Additionally, uncertainties in RPP values themselves can affect reconstruction success and could be leading to the persistent overrepresentation of tree taxa despite the application of REVEALS. Tree cover reconstructions tend to have higher certainty compared to taxon-specific reconstructions, as they are based on aggregation across taxa. However, the static latitudinal arboreal threshold for Betulaceae, *Betula*, and *Alnus* poses a limitation in our reconstruction. This could be improved by incorporating a dynamic, climate-dependent threshold in future work.

Validating pollen-based tree cover estimates with remote sensing-derived forest cover also presents a challenge. One key issue ~~is~~ are the inherent errors associated with remote sensing forest cover data. While validation using other sensors is possible, only a limited subset of the available data is cross-validated with Lidar data, which itself is characterized by limited spatial coverage (Sexton et al., 2013). A critical limitation of surface reflectance methods, as used in the Landsat-based forest cover, is their reliance on a 2D perspective, primarily capturing the forest canopy. This means that the understory is often not detected, resulting in an incomplete representation of the forest structure. In contrast, pollen-based estimates provide a more comprehensive, stratified view of the vegetation, as they incorporate all contributing taxa, not just the tree canopy. Despite this broader scope, pollen data and REVEALS estimates tend to emphasize trees more than other vegetation types consistently as is evident in the validations. Few records in central Europe pose an exception to this where forest cover seems to be slightly underestimated (see Fig. 9). Furthermore, pollen-based estimates are derived from records that span a much longer timescale than the modern forest cover data available, even though modern timeslices are used for validation. Increased anthropogenic impact could exacerbate discrepancies between pollen-based and remote-sensing estimates. This could contribute to the overestimation of forest cover, which persists in all continents. Additionally, these modern and arguably unnatural vegetation conditions may not correspond to past vegetation and may therefore have reduced significance for the reconstruction of past, natural landscapes.

Another challenge lies in validating the compositional reconstruction results. It remains uncertain whether RPP values have remained stable over time, and historical compositional data are not only scarce but also likely too recent to test this assumption effectively (Baker et al., 2016). Validating modern compositional reconstructions on large spatial scales is therefore difficult. As global compositional vegetation data are not readily available, remote sensing of tree cover serves as the best option for validation. But even with accurate tree cover reconstructions, uncertainties remain regarding the abundance of individual taxa due to the aggregated nature of the tree cover measure. To address this issue, global syntheses of tree and plant inventories or compositional remote sensing products could provide more robust validation. Additionally, vegetational compositions derived from sedimentary ancient DNA (sedaDNA) offer a promising avenue for comparing past vegetation data. Local quantitative sedaDNA vegetation signals could be averaged across multiple records to compare with pollen-based results (Niemeyer et al., 2017; Capo et al., 2021).

Lastly, the reconstructions are subject to certain limitations inherent in sedimentary pollen data, such as age uncertainty, temporal mixing, and irregular spatial and temporal resolution of records. Age uncertainty has been addressed as effectively as possible through consistent age modeling of the pollen dataset (Li et al., 2022a; **?**). However, replicating sediment and peat cores could generally provide more accurate estimates of record variability. Moreover, sampling more large lakes and ensuring precise dating would improve spatial coverage. Further, additional RPP studies are necessary to provide more accurate RPP estimates, including the development of regional RPP datasets to enhance reconstruction accuracy. This is especially the case in North America.

4.3 Outlook

The REVEALS tree cover reconstructions presented here offers insight into past vegetation changes and is a valuable alternative to already existing regional reconstructions, which follow different temporal and spatial aggregation methods. The Northern Hemisphere dataset provides an opportunity to explore past vegetation dynamics, gaining a deeper understanding of responses, trajectories, and potential feedback mechanisms. This is especially the case in Europe, whereas trend-based analyses should be the focus in North America and Asia. 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 help address unanswered questions about Holocene vegetation dynamics, including the deglacial forest conundrum (Dallmeyer et al., 2022; Strandberg et al., 2022). It could also serve as a valuable tool for validating Earth System Models that require extensive time series and vegetation data for accurate predictions (Dallmeyer et al., 2023). Comparing modeled vegetation to reconstructed vegetation could help uncover missing dynamics in coupled climate-vegetation models and new insights gained from these applications could enhance our ability to predict future changes.

5 Conclusions

We present data sets of reconstructed past plant cover and tree 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 tree cover compared to pollen percentages is achieved in all continents and reconstruction errors in Europe are lower compared to previous reconstructions. However, strong overestimation of tree cover persisted in North America and Asia highlighting the need for improved regional RPP syntheses. Extensive 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 (~~PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.961588). 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.13902976, 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	15.22	0.623	3	0.014	-	-	-	-	-	-	-	-	15.22	0.623	3	0.014
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

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.

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References

Anderson, N. J., Bugmann, H., Dearing, J. A., and Gaillard, M.-J.: Linking palaeoenvironmental data and models to understand the past and to predict the future, Trends in Ecology & Evolution, 21, 696–704, https://doi.org/10.1016/j.tree.2006.09.005, 2006.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., and Lenton, T. M.: Exceeding 1.5°C global warming could trigger multiple climate tipping points, Science, 377, eabn7950, https://doi.org/10.1126/science.abn7950, publisher: American Association for the Advancement of Science, 2022.

Baker, A. G., Zimny, M., Keczyński, A., Bhagwat, S. A., Willis, K. J., and Latałowa, M.: Pollen productivity estimates from old-growth forest strongly differ from those obtained in cultural landscapes: Evidence from the Białowieża National Park, Poland, The Holocene, 26, 80–92, https://doi.org/10.1177/0959683615596822, publisher: SAGE Publications Ltd, 2016.

Bartlein, P. J., Harrison, S. P., Brewer, S., Connor, S., Davis, B. A. S., Gajewski, K., Guiot, J., Harrison-Prentice, T. I., Henderson, A., Peyron, O., Prentice, I. C., Scholze, M., Seppä, H., Shuman, B., Sugita, S., Thompson, R. S., Viau, A. E., Williams, J., and Wu, H.: Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis, Climate Dynamics, 37, 775–802, https://doi.org/10.1007/s00382-010-0904-1, 2011.

Binney, H. A., Gething, P. W., Nield, J. M., Sugita, S., and Edwards, M. E.: Tree line identification from pollen data: beyond the limit?, Journal of Biogeography, 38, 1792–1806, https://doi.org/10.1111/j.1365-2699.2011.02507.x, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1365-2699.2011.02507.x, 2011.

Broström, A., Nielsen, A. B., Gaillard, M.-J., Hjelle, K., Mazier, F., Binney, H., Bunting, J., Fyfe, R., Meltsov, V., Poska, A., Räsänen, S., Soepboer, W., von Stedingk, H., Suutari, H., and Sugita, S.: Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review, Vegetation History and Archaeobotany, 17, 461–478, https://doi.org/10.1007/s00334-008-0148-8, 2008.

Cao, X., Tian, F., Li, F., Gaillard, M.-J., Rudaya, N., Xu, Q., and Herzschuh, U.: Pollen-based quantitative land-cover reconstruction for northern Asia covering the last 40 ka cal BP, Climate of the Past, 15, 1503–1536, https://doi.org/10.5194/cp-15-1503-2019, publisher: Copernicus GmbH, 2019.

Cao, X., Tian, F., Andreev, A., Anderson, P. M., Lozhkin, A. V., Bezrukova, E., Ni, J., Rudaya, N., Stobbe, A., Wieczorek, M., and Herzschuh, U.: A taxonomically harmonized and temporally standardized fossil pollen dataset from Siberia covering the last 40 kyr, Earth System Science Data, 12, 119–135, https://doi.org/10.5194/essd-12-119-2020, publisher: Copernicus GmbH, 2020.

Cao, X.-Y., Herzschuh, U., Telford, R. J., and Ni, J.: A modern pollen–climate dataset from China and Mongolia: Assessing its potential for climate reconstruction, Review of Palaeobotany and Palynology, 211, 87–96, https://doi.org/10.1016/j.revpalbo.2014.08.007, 2014.

Capo, E., Giguet-Covex, C., Rouillard, A., Nota, K., Heintzman, P. D., Vuillemin, A., Ariztegui, D., Arnaud, F., Belle, S., Bertilsson, S., Bigler, C., Bindler, R., Brown, A. G., Clarke, C. L., Crump, S. E., Debroas, D., Englund, G., Ficetola, G. F., Garner, R. E., Gauthier, J., Gregory-Eaves, I., Heinecke, L., Herzschuh, U., Ibrahim, A., Kisand, V., Kjær, K. H., Lammers, Y., Littlefair, J., Messager, E., Monchamp, M.-E., Olajos, F., Orsi, W., Pedersen, M. W., Rijal, D. P., Rydberg, J., Spanbauer, T., Stoof-Leichsenring, K. R., Taberlet, P., Talas, L., Thomas, C., Walsh, D. A., Wang, Y., Willerslev, E., van Woerkom, A., Zimmermann, H. H., Coolen, M. J. L., Epp, L. S., Domaizon, I., G. Alsos, I., and Parducci, L.: Lake Sedimentary DNA Research on Past Terrestrial and Aquatic Biodiversity: Overview and Recommendations, Quaternary, 4, 6, https://doi.org/10.3390/quat4010006, number: 1 Publisher: Multidisciplinary Digital Publishing Institute, 2021.

Dallmeyer, A., Kleinen, T., Claussen, M., Weitzel, N., Cao, X., and Herzschuh, U.: The deglacial forest conundrum, Nature Communications, 13, 6035, https://doi.org/10.1038/s41467-022-33646-6, number: 1 Publisher: Nature Publishing Group, 2022.

Dallmeyer, A., Poska, A., Marquer, L., Seim, A., and Gaillard, M.-J.: The challenge of comparing pollen-based quantitative vegetation reconstructions with outputs from vegetation models – a European perspective, Climate of the Past, 19, 1531–1557, https://doi.org/10.5194/cp-19-1531-2023, publisher: Copernicus GmbH, 2023.

Davis, B. A. S., Collins, P. M., and Kaplan, J. O.: The age and post-glacial development of the modern European vegetation: a plant functional approach based on pollen data, Vegetation History and Archaeobotany, 24, 303–317, https://doi.org/10.1007/s00334-014-0476-9, 2015.

Davis, M. B.: On the theory of pollen analysis, American Journal of Science, 261, 897–912, https://doi.org/10.2475/ajs.261.10.897, publisher: American Journal of Science Section: Articles, 1963.

Dawson, A., Williams, J. W., Gaillard, M.-J., Goring, S. J., Pirzamanbein, B., Lindstrom, J., Anderson, R. S., Brunelle, A., Foster, D., Gajewski, K., Gavin, D. G., Lacourse, T., Minckley, T. A., Oswald, W., Shuman, B., and Whitlock, C.: Holocene land cover change in North America: continental trends, regional drivers, and implications for vegetation-atmosphere feedbacks, Climate of the Past Discussions, pp. 1–52, https://doi.org/10.5194/cp-2024-6, publisher: Copernicus GmbH, 2024.

Dearing, J., Braimoh, A., Reenberg, A., Turner, B., and van der Leeuw, S.: Complex Land Systems: the Need for Long Time Perspectives to Assess their Future, Ecology and Society, 15, https://doi.org/10.5751/ES-03645-150421, publisher: The Resilience Alliance, 2010.

Dearing, J. A., Bullock, S., Costanza, R., Dawson, T. P., Edwards, M. E., Poppy, G. M., and Smith, G. M.: Navigating the Perfect Storm: Research Strategies for Socialecological Systems in a Rapidly Evolving World, Environmental Management, 49, 767–775, https://doi.org/10.1007/s00267-012-9833-6, 2012.

ESA: Land Cover CCI Product User Guide Version 2., maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf, 2017.

Fagerlind, F.: The real signification of pollen diagrams., Botaniska Notiser, p. 40, 1952.

Fyfe, R. M., de Beaulieu, J.-L., Binney, H., Bradshaw, R. H. W., Brewer, S., Le Flao, A., Finsinger, W., Gaillard, M.-J., Giesecke, T., Gil-Romera, G., Grimm, E. C., Huntley, B., Kunes, P., Kühl, N., Leydet, M., Lotter, A. F., Tarasov, P. E., and Tonkov, S.: The European Pollen Database: past efforts and current activities, Vegetation History and Archaeobotany, 18, 417–424, https://doi.org/10.1007/s00334-009-0215-9, 2009.

Fyfe, R. M., Woodbridge, J., and Roberts, N.: From forest to farmland: pollen-inferred land cover change across Europe using the pseudobiomization approach, Global Change Biology, 21, 1197–1212, https://doi.org/10.1111/gcb.12776, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/gcb.12776, 2015.

Gaillard, M.-J., Sugita, S., Mazier, F., Trondman, A.-K., Broström, A., Hickler, T., Kaplan, J. O., Kjellström, E., Kokfelt, U., Kuneš, P., Lemmen, C., Miller, P., Olofsson, J., Poska, A., Rundgren, M., Smith, B., Strandberg, G., Fyfe, R., Nielsen, A. B., Alenius, T., Balakauskas, L., Barnekow, L., Birks, H. J. B., Bjune, A., Björkman, L., Giesecke, T., Hjelle, K., Kalnina, L., Kangur, M., van der Knaap, W. O., Koff, T., Lagerås, P., Latałowa, M., Leydet, M., Lechterbeck, J., Lindbladh, M., Odgaard, B., Peglar, S., Segerström, U., von Stedingk, H., and Seppä, H.: Holocene land-cover reconstructions for studies on land cover-climate feedbacks, Climate of the Past, 6, 483–499, https://doi.org/10.5194/cp-6-483-2010, publisher: Copernicus GmbH, 2010.

Geng, R., Andreev, A., Kruse, S., Heim, B., van Geffen, F., Pestryakova, L., Zakharov, E., Troeva, E., Shevtsova, I., Li, F., Zhao, Y., and Herzschuh, U.: Modern Pollen Assemblages From Lake Sediments and Soil in East Siberia and Relative Pollen Productivity Estimates for Major Taxa, Frontiers in Ecology and Evolution, 10, https://www.frontiersin.org/article/10.3389/fevo.2022.837857, 2022.

Giesecke, T., Ammann, B., and Brande, A.: Palynological richness and evenness: insights from the taxa accumulation curve, Vegetation History and Archaeobotany, 23, 217–228, https://doi.org/10.1007/s00334-014-0435-5, 2014.

Githumbi, E., Fyfe, R., Gaillard, M.-J., Trondman, A.-K., Mazier, F., Nielsen, A.-B., Poska, A., Sugita, S., Woodbridge, J., Azuara, J., Feurdean, A., Grindean, R., Lebreton, V., Marquer, L., Nebout-Combourieu, N., Stančikaitė, M., Tanţău, I., Tonkov, S., Shumilovskikh, L., and data contributors, L.: European pollen-based REVEALS land-cover reconstructions for the Holocene: methodology, mapping and potentials, Earth System Science Data, 14, 1581–1619, https://doi.org/10.5194/essd-14-1581-2022, publisher: Copernicus GmbH, 2022.

Harris, I., Osborn, T. J., Jones, P., and Lister, D.: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset, Scientific Data, 7, 109, https://doi.org/10.1038/s41597-020-0453-3, number: 1 Publisher: Nature Publishing Group, 2020.

Hellman, S., Gaillard, M.-J., Broström, A., and Sugita, S.: The REVEALS model, a new tool to estimate past regional plant abundance from pollen data in large lakes: validation in southern Sweden, Journal of Quaternary Science, 23, 21–42, https://doi.org/10.1002/jqs.1126, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jqs.1126, 2008a.

Hellman, S. E. V., Gaillard, M.-j., Broström, A., and Sugita, S.: Effects of the sampling design and selection of parameter values on pollen-based quantitative reconstructions of regional vegetation: a case study in southern Sweden using the REVEALS model, Vegetation History and Archaeobotany, 17, 445–459, https://doi.org/10.1007/s00334-008-0149-7, 2008b.

Herzschuh, U., Li, C., Böhmer, T., Postl, A. K., Heim, B., Andreev, A. A., Cao, X., Wieczorek, M., and Ni, J.: LegacyPollen 1.0: A taxonomically harmonized global Late Quaternary pollen dataset of 2831 records with standardized chronologies, Earth System Science Data Discussions, pp. 1–25, https://doi.org/10.5194/essd-2022-37, publisher: Copernicus GmbH, 2022.

Herzschuh, U., Böhmer, T., Li, C., and Cao, X.: Northern Hemisphere temperature and precipitation reconstruction from taxonomically harmonized pollen data set with revised chronologies using WA-PLS and MAT (LegacyClimate 1.0), https://doi.org/10.1594/PANGAEA.930512, artwork Size: 12 datasets Medium: application/zip Publisher: PANGAEA, 2023a.

Herzschuh, U., Böhmer, T., Li, C., Chevalier, M., Hébert, R., Dallmeyer, A., Cao, X., Bigelow, N. H., Nazarova, L., Novenko, E. Y., Park, J., Peyron, O., Rudaya, N. A., Schlütz, F., Shumilovskikh, L. S., Tarasov, P. E., Wang, Y., Wen, R., Xu, Q., and Zheng, Z.: LegacyClimate 1.0: a dataset of pollen-based climate reconstructions from 2594 Northern Hemisphere sites covering the last 30 kyr and beyond, Earth System Science Data, 15, 2235–2258, https://doi.org/10.5194/essd-15-2235-2023, publisher: Copernicus GmbH, 2023b.

Hjelle, K. L., Mehl, I. K., Sugita, S., and Andersen, G. L.: From pollen percentage to vegetation cover: evaluation of the Landscape Reconstruction Algorithm in western Norway, Journal of Quaternary Science, 30, 312–324, https://doi.org/10.1002/jqs.2769, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jqs.2769, 2015.

Huang, R., Xu, Q., Tian, F., Li, J., Wang, Y., and Hao, J.: Re-estimated relative pollen productivity of typical steppe and meadow steppe in Inner Mongolia, Quaternary Sciences, 41, 1727–1737, https://doi.org/10.11928/j.issn.1001-7410.2021.06.18, publisher: , 2021.

IPCC: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland., Tech. rep., Intergovernmental Panel on Climate Change (IPCC), https://www.ipcc.ch/report/ar6/syr/, 2023.

Jiang, F., Xu, Q., Zhang, S., Li, F., Zhang, K., Wang, M., Shen, W., Sun, Y., and Zhou, Z.: Relative pollen productivities of the major plant taxa of subtropical evergreen–deciduous mixed woodland in China, Journal of Quaternary Science, 35, 526–538, https://doi.org/10.1002/jqs.3197, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jqs.3197, 2020.

Lenton, T. M. and Williams, H. T. P.: On the origin of planetary-scale tipping points, Trends in Ecology & Evolution, 28, 380–382, https://doi.org/10.1016/j.tree.2013.06.001, 2013.

Li, B., Zhang, W., Fyfe, R., Fan, B., Wang, S., Xu, Q., Zhang, N., Ding, G., Yang, J., and Li, Y.: High-resolution quantitative vegetation reconstruction in the North China Plain during the early-to-middle Holocene using the REVEALS model, CATENA, 234, 107 577, https://doi.org/10.1016/j.catena.2023.107577, 2024a.

Li, C., Postl, A. K., Böhmer, T., Cao, X., Dolman, A. M., and Herzschuh, U.: Harmonized chronologies of a global late Quaternary pollen dataset (LegacyAge 1.0), Earth System Science Data, 14, 1331–1343, https://doi.org/10.5194/essd-14-1331-2022, publisher: Copernicus GmbH, 2022a.

Li, C., Böhmer, T., Cao, X., Zhou, B., Liao, M., Li, K., and Herzschuh, U.: LegacyPollen2.0: an updated global taxonomically and temporally standardized fossil pollen dataset of 3728 palynological records, https://doi.org/10.1594/PANGAEA.965907, 2024b.

Li, C., Dallmeyer, A., Ni, J., Chevalier, M., Willeit, M., Andreev, A. A., Cao, X., Schild, L., Heim, B., and Herzschuh, U.: Global biome changes over the last 21,000 years inferred from model-data comparisons, EGUsphere, pp. 1–26, https://doi.org/10.5194/egusphere-2024-1862, publisher: Copernicus GmbH, 2024c.

Li, F., Gaillard, M.-J., Sugita, S., Mazier, F., Xu, Q., Zhou, Z., Zhang, Y., Li, Y., and Laffly, D.: Relative pollen productivity estimates for major plant taxa of cultural landscapes in central eastern China, Vegetation History and Archaeobotany, 26, 587–605, https://doi.org/10.1007/s00334-017-0636-9, 2017.

Li, F., Gaillard, M.-J., Xu, Q., Bunting, M. J., Li, Y., Li, J., Mu, H., Lu, J., Zhang, P., Zhang, S., Cui, Q., Zhang, Y., and Shen, W.: A Review of Relative Pollen Productivity Estimates From Temperate China for Pollen-Based Quantitative Reconstruction of Past Plant Cover, Frontiers in Plant Science, 9, https://www.frontiersin.org/article/10.3389/fpls.2018.01214, 2018.

Li, F., Gaillard, M.-J., Cao, X., Herzschuh, U., Sugita, S., Ni, J., Zhao, Y., An, C., Huang, X., Li, Y., Liu, H., Sun, A., and Yao, Y.: Gridded pollen-based Holocene regional plant cover in temperate and northern subtropical China suitable for climate modelling, Earth System Science Data, 15, 95–112, https://doi.org/10.5194/essd-15-95-2023, publisher: Copernicus GmbH, 2023.

Li, M., Zhang, S., Shen, W., Zhang, R., Zhou, Z., and Xu, Q.: Relative pollen productivities of major woody plant taxa in deciduous broadleaved forest in the Ziwuling Mountains of the central Chinese Loess Plateau, Quaternary International, https://doi.org/10.1016/j.quaint.2022.03.010, 2022b.

Mazier, F., Gaillard, M. J., Kuneš, P., Sugita, S., Trondman, A. K., and Broström, A.: Testing the effect of site selection and parameter setting on REVEALS-model estimates of plant abundance using the Czech Quaternary Palynological Database, Review of Palaeobotany and Palynology, 187, 38–49, https://doi.org/10.1016/j.revpalbo.2012.07.017, 2012.

Mazier, F., Broström, A., Bragée, P., Fredh, D., Stenberg, L., Thiere, G., Sugita, S., and Hammarlund, D.: Two hundred years of land-use change in the South Swedish Uplands: comparison of historical map-based estimates with a pollen-based reconstruction using the landscape reconstruction algorithm, Vegetation History and Archaeobotany, 24, 555–570, https://doi.org/10.1007/s00334-015-0516-0, 2015.

Mottl, O., Flantua, S. G. A., Bhatta, K. P., Felde, V. A., Giesecke, T., Goring, S., Grimm, E. C., Haberle, S., Hooghiemstra, H., Ivory, S., Kuneš, P., Wolters, S., Seddon, A. W. R., and Williams, J. W.: Global acceleration in rates of vegetation change over the past 18,000 years, Science, 372, 860–864, https://doi.org/10.1126/science.abg1685, publisher: American Association for the Advancement of Science, 2021.

Nielsen, A. B., Giesecke, T., Theuerkauf, M., Feeser, I., Behre, K.-E., Beug, H.-J., Chen, S.-H., Christiansen, J., Dörfler, W., Endtmann, E., Jahns, S., de Klerk, P., Kühl, N., Latałowa, M., Odgaard, B. V., Rasmussen, P., Stockholm, J. R., Voigt, R., Wiethold, J., and Wolters, S.: Quantitative reconstructions of changes in regional openness in north-central Europe reveal new insights into old questions, Quaternary Science Reviews, 47, 131–149, https://doi.org/10.1016/j.quascirev.2012.05.011, 2012.

Niemeyer, B., Epp, L. S., Stoof-Leichsenring, K. R., Pestryakova, L. A., and Herzschuh, U.: A comparison of sedimentary DNA and pollen from lake sediments in recording vegetation composition at the Siberian treeline, Molecular Ecology Resources, 17, e46–e62, https://doi.org/10.1111/1755-0998.12689, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/1755-0998.12689, 2017.

Pirzamanbein, B., Lindström, J., Poska, A., Sugita, S., Trondman, A.-K., Fyfe, R., Mazier, F., Nielsen, A. B., Kaplan, J. O., Bjune, A. E., Birks, H. J. B., Giesecke, T., Kangur, M., Latałowa, M., Marquer, L., Smith, B., and Gaillard, M.-J.: Creating spatially continuous maps of past land cover from point estimates: A new statistical approach applied to pollen data, Ecological Complexity, 20, 127–141, https://doi.org/10.1016/j.ecocom.2014.09.005, 2014.

Prentice, C.: Records of vegetation in time and space: the principles of pollen analysis, in: Vegetation history, edited by Huntley, B. and Webb, T., Handbook of vegetation science, pp. 17–42, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-94-009-3081-0_2, 1988.

Prentice, C., Guiot, J., Huntley, B., Jolly, D., and Cheddadi, R.: Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka, Climate Dynamics, 12, 185–194, https://doi.org/10.1007/BF00211617, 1996.

Prentice, I. C.: Pollen representation, source area, and basin size: Toward a unified theory of pollen analysis, Quaternary Research, 23, 76–86, https://doi.org/10.1016/0033-5894(85)90073-0, 1985.

Prentice, I. C. and Webb III, T.: Pollen percentages, tree abundances and the Fagerlind effect, Journal of Quaternary Science, 1, 35–43, https://doi.org/10.1002/jqs.3390010105, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/jqs.3390010105, 1986.

Roberts, N., Fyfe, R. M., Woodbridge, J., Gaillard, M.-J., Davis, B. a. S., Kaplan, J. O., Marquer, L., Mazier, F., Nielsen, A. B., Sugita, S., Trondman, A.-K., and Leydet, M.: Europe's lost forests: a pollen-based synthesis for the last 11,000 years, Scientific Reports, 8, 716, https://doi.org/10.1038/s41598-017-18646-7, number: 1 Publisher: Nature Publishing Group, 2018.

Schild, L. and Ewald, P.: [Analysis code] LegacyVegetation 1.0: Global reconstruction of vegetation compositions and forest cover from pollen archives of the last 50 ka, https://doi.org/10.5281/zenodo.10191859, 2023.

Serge, M. A., Mazier, F., Fyfe, R., Gaillard, M.-J., Klein, T., Lagnoux, A., Galop, D., Githumbi, E., Mindrescu, M., Nielsen, A. B., Trondman, A.-K., Poska, A., Sugita, S., Woodbridge, J., Abel-Schaad, D., Åkesson, C., Alenius, T., Ammann, B., Andersen, S. T., Anderson, R. S., Andrič, M., Balakauskas, L., Barnekow, L., Batalova, V., Bergman, J., Birks, H. J. B., Björkman, L., Bjune, A. E., Borisova, O., Broothaerts, N., Carrion, J., Caseldine, C., Christiansen, J., Cui, Q., Currás, A., Czerwiński, S., David, R., Davies, A. L., De Jong, R., Di Rita, F., Dietre, B., Dörfler, W., Doyen, E., Edwards, K. J., Ejarque, A., Endtmann, E., Etienne, D., Faure, E., Feeser, I., Feurdean, A., Fischer, E., Fletcher, W., Franco-Múgica, F., Fredh, E. D., Froyd, C., Garcés-Pastor, S., García-Moreiras, I., Gauthier, E., Gil-Romera, G., González-Sampériz, P., Grant, M. J., Grindean, R., Haas, J. N., Hannon, G., Heather, A.-J., Heikkilä, M., Hjelle, K., Jahns, S., Jasiunas, N., Jiménez-Moreno, G., Jouffroy-Bapicot, I., Kabailienė, M., Kamerling, I. M., Kangur, M., Karpińska-Kołaczek, M., Kasianova, A., Kołaczek, P., Lagerås, P., Latalowa, M., Lechterbeck, J., Leroyer, C., Leydet, M., Lindbladh, M., Lisitsyna, O., López-Sáez, J.-A., Lowe, J., Luelmo-Lautenschlaeger, R., Lukanina, E., Macijauskaitė, L., Magri, D., Marguerie, D., Marquer, L., Martinez-Cortizas, A., Mehl, I., Mesa-Fernández, J. M., Mighall, T., Miola, A., Miras, Y., Morales-Molino, C., Mrotzek, A., Sobrino, C. M., Odgaard, B., Ozola, I., Pérez-Díaz, S., Pérez-Obiol, R. P., Poggi, C., Rego, P. R., Ramos-Román, M. J., Rasmussen, P., Reille, M., Rösch, M., Ruffaldi, P., Goni, M. S., Savukynienė, N., Schröder, T., Schult, M., Segerström, U., Seppä, H., Vives, G. S., Shumilovskikh, L., Smettan, H. W., Stancikaite, M., Stevenson, A. C., Stivrins, N., Tantau, I., Theuerkauf, M., Tonkov, S., van der Knaap, W. O., van Leeuwen, J. F. N., Vecmane, E., Verstraeten, G., Veski, S., Voigt, R., Von Stedingk, H., Waller, M. P., Wiethold, J., Willis, K. J., Wolters, S., and Zernitskaya, V. P.: Testing the Effect of Relative Pollen Productivity on the REVEALS Model: A Validated Reconstruction of Europe-Wide Holocene Vegetation, Land, 12, 986, https://doi.org/10.3390/land12050986, number: 5 Publisher: Multidisciplinary Digital Publishing Institute, 2023.

Sexton, J. O., Song, X.-P., Feng, M., Noojipady, P., Anand, A., Huang, C., Kim, D.-H., Collins, K. M., Channan, S., DiMiceli, C., and Townshend, J. R.: Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error, International Journal of Digital Earth, 6, 427–448, https://doi.org/10.1080/17538947.2013.786146, publisher: Taylor & Francis _eprint: https://doi.org/10.1080/17538947.2013.786146, 2013.

Shakun, J. D., Clark, P. U., He, F., Marcott, S. A., Mix, A. C., Liu, Z., Otto-Bliesner, B., Schmittner, A., and Bard, E.: Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation, Nature, 484, 49–54, https://doi.org/10.1038/nature10915, publisher: Nature Publishing Group, 2012.

Soepboer, W., Sugita, S., and Lotter, A. F.: Regional vegetation-cover changes on the Swiss Plateau during the past two millennia: A pollen-based reconstruction using the REVEALS model, Quaternary Science Reviews, 29, 472–483, https://doi.org/10.1016/j.quascirev.2009.09.027, 2010.

Strandberg, G., Kjellström, E., Poska, A., Wagner, S., Gaillard, M.-J., Trondman, A.-K., Mauri, A., Davis, B. a. S., Kaplan, J. O., Birks, H. J. B., Bjune, A. E., Fyfe, R., Giesecke, T., Kalnina, L., Kangur, M., van der Knaap, W. O., Kokfelt, U., Kuneš, P., Lata\l owa, M., Marquer, L., Mazier, F., Nielsen, A. B., Smith, B., Seppä, H., and Sugita, S.: Regional climate model simulations for Europe at 6 and 0.2 k BP: sensitivity to changes in anthropogenic deforestation, Climate of the Past, 10, 661–680, https://doi.org/10.5194/cp-10-661-2014, publisher: Copernicus GmbH, 2014.

Strandberg, G., Lindström, J., Poska, A., Zhang, Q., Fyfe, R., Githumbi, E., Kjellström, E., Mazier, F., Nielsen, A. B., Sugita, S., Trondman, A.-K., Woodbridge, J., and Gaillard, M.-J.: Mid-Holocene European climate revisited: New high-resolution regional climate model simulations using pollen-based land-cover, Quaternary Science Reviews, 281, 107 431, https://doi.org/10.1016/j.quascirev.2022.107431, 2022.

Strandberg, G., Chen, J., Fyfe, R., Kjellström, E., Lindström, J., Poska, A., Zhang, Q., and Gaillard, M.-J.: Did the Bronze Age deforestation of Europe affect its climate? A regional climate model study using pollen-based land cover reconstructions, Climate of the Past, 19, 1507–1530, https://doi.org/10.5194/cp-19-1507-2023, publisher: Copernicus GmbH, 2023.

Stuart, A. and Ord, J.: Kendall's Advanced Theory of Statistic, vol. Vol. 1 of *Distribution Theory*, Edward Arnold, London, 1994.

Sugita, S.: A Model of Pollen Source Area for an Entire Lake Surface, Quaternary Research, 39, 239–244, https://doi.org/10.1006/qres.1993.1027, 1993.

Sugita, S.: Theory of quantitative reconstruction of vegetation I: pollen from large sites REVEALS regional vegetation composition, The Holocene, 17, 229–241, https://doi.org/10.1177/0959683607075837, publisher: SAGE Publications Ltd, 2007.

Sugita, S., Parshall, T., Calcote, R., and Walker, K.: Testing the Landscape Reconstruction Algorithm for spatially explicit reconstruction of vegetation in northern Michigan and Wisconsin, Quaternary Research, 74, 289–300, https://doi.org/10.1016/j.yqres.2010.07.008, publisher: Cambridge University Press, 2010.

Theuerkauf, M., Couwenberg, J., Kuparinen, A., and Liebscher, V.: A matter of dispersal: REVEALSinR introduces state-of-the-art dispersal models to quantitative vegetation reconstruction, Vegetation History and Archaeobotany, 25, 541–553, https://doi.org/10.1007/s00334-016-0572-0, 2016.

Tian, F., Cao, X., Dallmeyer, A., Ni, J., Zhao, Y., Wang, Y., and Herzschuh, U.: Quantitative woody cover reconstructions from eastern continental Asia of the last 22 kyr reveal strong regional peculiarities, Quaternary Science Reviews, 137, 33–44, https://doi.org/10.1016/j.quascirev.2016.02.001, 2016.

Townshend, J.: Global Forest Cover Change (GFCC) Tree Cover Multi-Year Global 30 m V003, https://doi.org/10.5067/MEASURES/GFCC/GFCC30TC.003, 2016.

Trondman, A.-K., Gaillard, M.-J., Mazier, F., Sugita, S., Fyfe, R., Nielsen, A. B., Twiddle, C., Barratt, P., Birks, H. J. B., Bjune, A. E., Björkman, L., Broström, A., Caseldine, C., David, R., Dodson, J., Dörfler, W., Fischer, E., van Geel, B., Giesecke, T., Hultberg, T., Kalnina, L., Kangur, M., van der Knaap, P., Koff, T., Kuneš, P., Lagerås, P., Latałowa, M., Lechterbeck, J., Leroyer, C., Leydet, M., Lindbladh, M., Marquer, L., Mitchell, F. J. G., Odgaard, B. V., Peglar, S. M., Persson, T., Poska, A., Rösch, M., Seppä, H., Veski, S., and Wick, L.: Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling, Global Change Biology, 21, 676–697, https://doi.org/10.1111/gcb.12737, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/gcb.12737, 2015.

Trondman, A.-K., Gaillard, M.-J., Sugita, S., Björkman, L., Greisman, A., Hultberg, T., Lagerås, P., Lindbladh, M., and Mazier, F.: Are pollen records from small sites appropriate for REVEALS model-based quantitative reconstructions of past regional vegetation? An empirical test in southern Sweden, Vegetation History and Archaeobotany, 25, 131–151, https://doi.org/10.1007/s00334-015-0536-9, 2016.

Viau, A. E., Ladd, M., and Gajewski, K.: The climate of North America during the past 2000 years reconstructed from pollen data, Global and Planetary Change, 84-85, 75–83, https://doi.org/10.1016/j.gloplacha.2011.09.010, 2012.

Vincens, A., Lézine, A.-M., Buchet, G., Lewden, D., and Le Thomas, A.: African pollen database inventory of tree and shrub pollen types, Review of Palaeobotany and Palynology, 145, 135–141, https://doi.org/10.1016/j.revpalbo.2006.09.004, 2007.

Wan, Q., Zhang, Y., Huang, K., Sun, Q., Zhang, X., Gaillard, M.-J., Xu, Q., Li, F., and Zheng, Z.: Evaluating quantitative pollen representation of vegetation in the tropics: A case study on the Hainan Island, tropical China, Ecological Indicators, 114, 106 297, https://doi.org/10.1016/j.ecolind.2020.106297, 2020.

Wan, Q., Huang, K., Chen, C., Tang, Y., Zhang, X., Zhang, Z., and Zheng, Z.: Relative Pollen Productivity Estimates for Major Plant Taxa in Middle Subtropical China, Land, 12, 1337, https://doi.org/10.3390/land12071337, number: 7 Publisher: Multidisciplinary Digital Publishing Institute, 2023.

Wang, Y., Xu, Q., Zhang, S., Sun, Y., Li, Y., Hao, J., Huang, R., Shi, J., Wang, N., Wang, T., Li, Y., Zhang, R., Zhang, X., and Zhou, Z.: Relative pollen productivity estimates and landcover reconstruction of desert steppe in arid Western China: An example in Barkol Basin, Quaternary Sciences, 41, 1738–1748, https://doi.org/10.11928/j.issn.1001-7410.2021.06.19, publisher: , 2021.

Webb, T., Howe, S. E., Bradshaw, R. H. W., and Heide, K. M.: Estimating plant abundances from pollen percentages: The use of regression analysis, Review of Palaeobotany and Palynology, 34, 269–300, https://doi.org/10.1016/0034-6667(81)90046-4, 1981.

Whitmore, J., Gajewski, K., Sawada, M., Williams, J. W., Shuman, B., Bartlein, P. J., Minckley, T., Viau, A. E., Webb, T., Shafer, S., Anderson, P., and Brubaker, L.: Modern pollen data from North America and Greenland for multi-scale paleoenvironmental applications, Quaternary Science Reviews, 24, 1828–1848, https://doi.org/10.1016/j.quascirev.2005.03.005, 2005.

Wieczorek, M. and Herzschuh, U.: Compilation of relative pollen productivity (RPP) estimates and taxonomically harmonised RPP datasets for single continents and Northern Hemisphere extratropics, Earth System Science Data, 12, 3515–3528, https://doi.org/10.5194/essd-12-3515-2020, publisher: Copernicus GmbH, 2020.

Williams, J. W., Grimm, E. C., Blois, J. L., Charles, D. F., Davis, E. B., Goring, S. J., Graham, R. W., Smith, A. J., Anderson, M., Arroyo-Cabrales, J., Ashworth, A. C., Betancourt, J. L., Bills, B. W., Booth, R. K., Buckland, P. I., Curry, B. B., Giesecke, T., Jackson, S. T., Latorre, C., Nichols, J., Purdum, T., Roth, R. E., Stryker, M., and Takahara, H.: The Neotoma Paleoecology Database, a multiproxy, international, community-curated data resource, Quaternary Research, 89, 156–177, https://doi.org/10.1017/qua.2017.105, publisher: Cambridge University Press, 2018.

Woodbridge, J., Fyfe, R. M., and Roberts, N.: A comparison of remotely sensed and pollen-based approaches to mapping Europe's land cover, Journal of Biogeography, 41, 2080–2092, https://doi.org/10.1111/jbi.12353, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/jbi.12353, 2014.

Zhang, N., Ge, Y., Li, Y., Li, B., Zhang, R., Zhang, Z., Fan, B., Zhang, W., and Ding, G.: Modern pollen-vegetation relationships in the Taihang Mountains: Towards the quantitative reconstruction of land-cover changes in the North China Plain, Ecological Indicators, 129, 107 928, https://doi.org/10.1016/j.ecolind.2021.107928, 2021a.

Zhang, Y., Wei, Q., Zhang, Z., Xu, Q., Gao, W., and Li, Y.: Relative pollen productivity estimates of major plant taxa and relevant source area of pollen in the warm-temperate forest landscape of northern China, Vegetation History and Archaeobotany, 30, 231–241, https://doi.org/10.1007/s00334-020-00779-x, 2021b.