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Harmonized chronologies of a global late Quaternary pollen dataset (LegacyAge 1.0)

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Abstract. Although numerous pollen records are available worldwide in various databases, their use for synthesis works is limited as the chronologies are, as yet, not harmonized globally, and temporal uncertainties are unknown. We present a chronology framework named LegacyAge 1.0 that includes harmonized chronologies of 2831 palynological records (out of 3471 available records), downloaded from the Neotoma Paleoecology Database (last access: April 2021) and 324 additional Asian records. All chronologies use the Bayesian framework implemented in Bacon version 2.5.3. Optimal parameter settings of priors (accumulation.shape, memory.strength, memory.mean, accumulation.rate, thickness) were identified based on previous experiences or iteratively after preliminary model inspection. The most common control points for the chronologies are radiocarbon dates (86.1%), calibrated by the latest calibration curves (IntCal20 and SHcal20 for the terrestrial radiocarbon dates in the northern and southern hemispheres; Marine20 for marine materials). The original literature was consulted when dealing with obvious outliers and inconsistencies. Several major challenges when setting up the

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chronologies included the waterline issue (18.8% of records), reservoir effect (4.9%), and sediment deposition discontinuity (4.4%). Finally, we numerically compare the LegacyAge 1.0 chronologies to the original ones and show that the chronologies of 95.4% of records could be improved according to our assessment. Our chronology framework and revised chronologies provide the opportunity to make use of the ages and age uncertainties in synthesis studies of, for example, pollen-based vegetation and climate change. The LegacyAge 1.0 dataset and R code used are open-access and available at PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.933132; Li et al., 2021) and Github (https://github.com/LongtermEcology/LegacyAge-1.0), respectively.

1 Introduction

Global and continental fossil pollen databases are used for a variety of paleoenvironmental studies, such as past climate and biome reconstructions, palaeo-model validation, and the assessment of human-environmental interactions (Gajewski, 2008; Gaillard et al., 2010; Cao et al., 2013; Mauri et al., 2015; Trondman et al., 2015; Marsicek et al., 2018; Herzschuh et al., 2019). Several fossil pollen databases have been successfully established (Gajewski, 2008; Fyfe et al., 2009), such as the European Pollen Database (http://www.europeanpollendatabase.net), the North American Pollen Database (http://www.ncdc.noaa.gov/paleo/napd.html), and the Latin American Pollen Database (http://www.latinamericapollendb.com); most of these data are now included in the Neotoma Paleoecology Database (https://www.neotomadb.org/; Williams et al., 2018). Chronologies and control points are stored in these databases along with the pollen records. However, the inference of temporal uncertainty remains a challenge because they are based on calibrated and uncalibrated ^{14}C ages and were established using various methodologies (Blois et al., 2011; Giesecke et al., 2014; Flantua et al., 2016; Trachsel and Telford, 2017). Recently, the need for harmonized chronologies and an identical inference of temporal uncertainties have increased as studies are looking for spatiotemporal patterns using multi-record analyses (Jennerjahn et al., 2004; Blaauw et al., 2007; Giesecke et al., 2011; Flantua et al., 2016). Accordingly, some efforts have been made to harmonize the chronologies for part of the data stored in the databases (Fyfe et al., 2009; Blois et al., 2011; Giesecke et al., 2011; Giesecke et al., 2014; Flantua et al., 2016; Brewer et al., 2017; Wang et al., 2019; Mottl et al., 2021). However, a harmonized chronology framework is needed, not only to allow for the consistent inference of age and age uncertainties but also to apply to newly published records or one that can be adjusted to the specific requirement of a study.

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Here we present the rationale and code for the chronology framework named LegacyAge 1.0, as well as the metadata, and parameter settings of 2831 palynological records from the Neotoma Paleoecology Database (last access: April 2021) and 324 additional Asian records that were recently synthesized (Cao et al., 2013, 2020). We also report on the major challenges when setting up the chronologies and assess the quality of the LegacyAge 1.0 chronologies. Finally, the newly harmonized chronologies are numerically compared with the original ones. All data and R code used for this study are open-access and available at PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.933132; Li et al., 2021) and Github (https://github.com/LongtermEcology/LegacyAge-1.0), respectively.

2 Methods

2.1 Data sources

We established chronologies for the 'Global taxonomically harmonized pollen data collection with revised chronologies' (https://doi.pangaea.de/10.1594/PANGAEA.929773; Herzschuh et al., 2021), which comprises 3471 records (3147 records from Neotoma (last access: April 2021) and 324 records from Asian datasets). Records were obtained from lake sediments (49.4%), peatlands (34.3%), and other archives (16.3%) (Fig. 1). As the spatial coverage of records in certain regions is poor, for example, in China and Siberia, records compiled by Cao et al. (2013, 2020) and our own collection (AWI) were included. The following chronology metadata were collected for each record: *Event, Data_Source, Site_ID, Dataset_ID, Site_name, Location (longitude, latitude, elevation, and continent), Archive_Type, Site_Description, Reference, Laboratory number of dating, Dating_Method, Material_Dated, Date (age, error older, error younger, depth, thickness), Additional relevant comments from authors (e.g., reservoir effect, hiatus, outliers, and date rejected), Original chronologies (name, age type (calibrated or uncalibrated radiocarbon years BP), age model, estimated age (age older, age, age younger), control points (e.g., core top, core bottom, and control point type)).* This dataset is available at https://doi.pangaea.de/10.1594/PANGAEA.933132 (Li et al., 2021).

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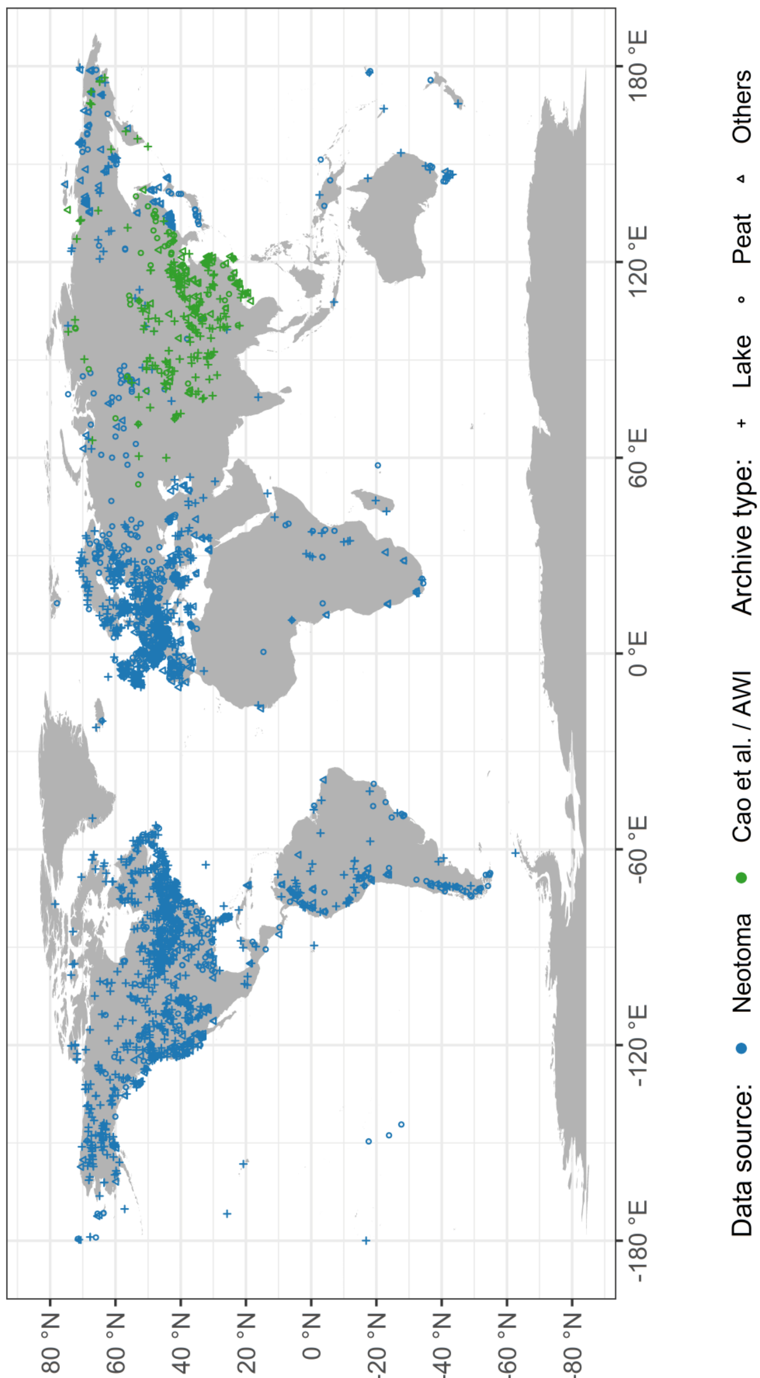

Figure 1. Map of records by source and archive type.

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2.2 Chronological control points

2.2.1 Radiometric dates

Radiocarbon dating: most records are dated by radiocarbon method (^{14}C dating, conventional or accelerator mass spectrometry), which is one of the most commonly used dating techniques as it covers the time range of most pollen records (ca. the last 50 ka BP (before present)). However, ^{14}C dates can appear to be too old or too young due to various effects such as the reservoir effect, contamination, and insufficient carbon, which have to be considered when setting up the chronologies (Roberts, 2013).

Lead-210 dating: the uppermost part of some lake records have been dated using a radioactive isotope of lead (lead-210), which has a half-life of 22.3 years and provides useful age control for the last 100-150 years (Appleby and Oldfield, 1978; Cuney, 2021).

Luminescence dating: archaeological materials, loess, and river sediments have often been dated via luminescence, including thermoluminescence (TL) and optically stimulated luminescence (OSL). These dating techniques cover time-scales from millennia to hundreds of thousands of years (Roberts, 2013; Cuney, 2021).

2.2.2 Lithological dates

Varve dating: varve chronology, generated from counting varves, is considered a relatively accurate dating method for the late Quaternary, particularly for the Holocene (Ojala et al., 2012; Zolitschka et al., 2015; Ramisch et al., 2020). All samples are considered as control points. If a pollen record has a varve chronology stored and assessed in the Varved Sediments Database (VARDA, https://varve.gfz-potsdam.de/), we generally preferred to use it over chronologies based on other dating techniques.

Tephrochronology: tephra layers are used as isochrones to correlate and synchronize sequences at a regional or continental scale (Lowe, 2011). Tephras documented in the Global Tephrochronological Database (Tephrabase, https://www.tephrabase.org/) were included to improve the chronologies (in accordance with Giesecke et al., 2014), such as the Mazama ash (7630+-40 cal. yr BP (where ‘present’ is 1950 CE); Brown and Hebda, 2003), Vedde ash (12121+-57 cal. yr BP; Lane et al., 2012), and the Laacher See ash (12880+-120 cal. yr BP).

2.2.3 Biostratigraphical dates

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Biostratigraphical dates have been widely relied on before ^{14}C dating became available and affordable (Bardossy and Fodor, 2013). Since the biostratigraphic schemes are updated by new records, improved dating, and taxonomic revision (Flantua et al., 2016), most of them were rejected when we harmonized the chronologies. However, a few well-known and widely applicable biostratigraphic boundaries (Rasmussen et al., 2014) were used if the chronologies could not be sufficiently constrained by other dating techniques, for example, the Younger Dryas/Holocene (11500±250 cal. yr BP), Allerød/Younger Dryas (12650±250 cal. yr BP), and Oldest Dryas/Bølling (14650±250 cal. yr BP; Giesecke et al., 2014).

2.3 Establishing the chronologies

2.3.1 Method choice

Establishing age-depth relationships is necessary because sediment cores typically have fewer chronological control points than samples and to account for dating uncertainty. A number of methods are available including linear interpolation, smoothing spline, OxCal, Bchron, and Bacon (Bennett and Fuller, 2002; Blaauw, 2010; Blaauw and Heegaard, 2012; Flantua et al., 2016; Sánchez Goñi et al., 2017; Trachsel and Telford, 2017; Blaauw et al., 2018). Bacon is one of the most commonly used methods for age-depth modeling that 'uses Bayesian statistics to reconstruct Bayesian accumulation histories for deposits, through combining radiocarbon and other dates with prior information' (Blaauw and Christen, 2011). The collection of additional information, on the geological and hydrological setting as well as the environmental history (Giesecke et al., 2014), helps to constrain the chronologies, although it is time-consuming for large datasets. Through millions of Markov Chain Monte Carlo (MCMC) iterations, Bacon provides the calibrated ages (mean, median, minimum, maximum) at each depth (e.g., every centimeter) with a 95% confidence intervals and an indication of how well the model fits the dates, although it needs much supervision and computing power. The confidence interval guides the overall trend of the age-depth relationships, so the control points guide rather than strictly constrain the age-depth relationships (Giesecke et al., 2014). Bacon version 2.3.3 and later (Blaauw and Christen, 2011) can also handle sudden shifts in the accumulation rate when given the hiatus/boundary depth and resetting the memory to 0 when crossing the hiatus. Therefore, all age-depth relationships in our dataset will be constructed using the latest Bacon version 2.5.3 (Blaauw and Christen, 2011; Blaauw et al., 2018) in R (R Core Team, 2021).

2.3.2 Core tops and basal ages

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Wherever possible, the record-related publications were read to decide whether the core top was modern at the time of sampling. For modern core-tops, if the core was collected from sites where sediment was still accumulating, the sediment surface could be assigned to the year of sampling, adding one significant time control for the chronologies. If the sampling date was unavailable, an alternative surface age from the original chronology in Neotoma was added at the core top. For core-tops judged not to be modern, we inferred the surface age from the calibrated age-depth model. For basal ages, when the calibrated age-depth model for the lowermost profile has considerable extrapolation and was not sufficiently constrained by the control points, we also accepted the prior information of core basal age from the record-related publications or Neotoma. Moreover, the highest (lowest) depth of the model was defined by the first (last) dating or pollen sample.

2.3.3 Calibration curves

To transform the measured ^{14}C ages to calendar ages, the latest calibration curves were used (Hajdas, 2014): IntCal20 (Reimer et al., 2020) and SHcal20 (Hogg et al., 2020) to calibrate the terrestrial radiocarbon dates in the northern and southern hemispheres, respectively; and Marine20 (Heaton et al., 2020) for the 38 marine records included in our dataset although it does not distinguish between the northern and southern hemisphere (Sánchez Goñi et al., 2017). Absolute dates (e.g., lead-210, OSL, tephra), already presented on the calendar scale, were not calibrated (Blaauw and Christen, 2011). Modern/post-bomb ^{14}C dates (negative ^{14}C ages) were calibrated using appropriate post-bomb calibration curves (post-bomb=1 for >40°N; 2 for 0°-40°N; 4 for southern hemisphere; Hua et al., 2013).

2.3.4 Parameter settings for the initial Bacon run

After consultation of the relevant literature (Blaauw and Christen, 2011; Goring et al., 2012; Cao et al., 2013; Fiałkiewicz-kozieł et al., 2014; Blaauw et al., 2018) and assessments of several runs with a test set of records, we set the following Bacon parameters. (1) The prior for the accumulation rate consists of a gamma distribution with two parameters, **mean accumulation rate** (acc.rate) and **accumulation shape** (acc.shape). For the acc.shape, we accepted its default value of 1.5 as higher values resulted in a more peaked shape of the gamma distribution. A first approximation of the acc.mean was calculated as the average accumulation rate between the first and the last date of each record, combined with the prior information of dates, which is more reasonable than using a constant value (default acc.mean=20 yr/cm). (2) The **section thickness** (default thick=5) significantly affects the flexibility

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of the age-depth model. Blaauw and Christen (2011) indicated that models with few sections tend to show more abrupt changes in accumulation rate, while models with many sections usually appear smoother but are computationally more intense. We tested six thicknesses (2.5 cm, 5 cm, 10 cm, 30 sections, 60 sections, and 120 sections) with and without an artificial surface age, thereby generating 12 age models for each core. (3) The memory, that is, the dependence of accumulation rate between neighboring depths, is a beta distribution defined by two parameters: **memory strength** (mem.strength; default 10) and **mean memory** (mem.mean; default 0.5). For the mem.strength, we used a value of 20 as suggested by Goring et al. (2012), which allows a large range of posterior memory values. We set different mem.mean values (0.3 for lake and 0.7 for peatland) to accommodate differences in accumulation conditions between lakes and peatland, where the higher memory for peatlands implies a more constant accumulation history (Blaauw and Christen, 2011; Goring et al., 2012; Cao et al., 2013; Cao et al., 2020).

In addition to the major parameters mentioned above, we also adjusted several specific parameters for some records according to prior information collected from record-related publications or Neotoma (this table is available in PANGAEA). (1) **Freshwater reservoir effects:** the uptake of old carbon by aquatic plants, the 'hard-water effect' or slow CO_2 exchange between the atmosphere and water, can result in too old radiocarbon dates (Philippsen, 2013; Philippsen and Heinemeier, 2013). In addition to the reservoir ages reported by the original authors, we also identified some additional records, where the authors may have ignored them via modern correction and linear extrapolation (Wang et al., 2017). We then subtracted the reservoir age from all ^{14}C dates of an affected record as a constant. We may have underestimated the number of such records due to the difficulty of estimating the reservoir age where the sediment surface was eroded or used for agricultural purposes. (2) **Waterline issues:** stratigraphic records do not always start at a depth of 0 cm, for example, if the uppermost part of the core is lost, if the record is only a part of a longer sequence, or if the depths are measured from the water surface instead of the sediment surface, leading to the so-called waterline issue. Accordingly, we adjusted the uppermost depth of the chronology based on prior information collected from the original publications and Neotoma. (3) **Hiatuses:** where the sediment deposition was not continuous, Bacon resets the memory to 0, causing a break in auto-correlated in the accumulation rate for depths before and after the hiatus (Blaauw and Christen, 2011). (4) **Dates rejected/added:** Neotoma usually reports all ^{14}C dates from cores, even when deemed inaccurate. We assessed and, if appropriate, a priori rejected the ^{14}C dates of samples with contaminated or insufficient carbon, or reworked sediments, in most cases following the suggestions in the original publications. We down-weighted

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the impact of outliers on the overall trend of the age-depth relationships and risked that age uncertainties were too optimistic. We also documented all lithological dates (e.g., varves and tephra) and biostratigraphical dates collected from the original publications and from Neotoma to supplement the chronology metadata.

2.3.5 Assessment of initial age-depth models and final parameter selection

For each record, 12 age models were visually assessed. Preference was given to models that fitted the dates well and with small uncertainties when choosing the 'best' model for each record (Blaauw and Christen, 2011; Blaauw et al., 2018). If necessary, we also adjusted the parameter settings such as the section thickness and accumulation rate to make a better fit with the dates that was consistent with prior information. For the final parameter settings used for each record, please see https://doi.pangaea.de/10.1594/PANGAEA.933132 (Li et al., 2021).

2.4 Evaluation of the newly generated age-depth models

For the temporal uncertainty of the age-depth models, we take used the 95% confidence intervals for age estimated by the Bacon model for each centimeter. These values are approximately twice the standard error of the estimated age at a given depth. We plotted our newly generated calibrated chronologies with 95% confidence intervals together with the original ones taken from the Neotoma and Cao et al. (2013, 2020) datasets to make comparisons and evaluate the performance of the new models.

3 Results

3.1 Overview of major challenges when establishing the chronologies

Age-depth models were initially established for all 3471 records. We discarded 640 records with fewer than 2 reliable dates and leaving chronologies for 2831 records. We faced several major challenges when establishing the chronologies. After assessments and consultation of prior information from original publications, we identified 139 records (4.9%) with reservoir effects, 533 records (18.8%) with waterline issues, 125 records (4.4%) with hiatuses, 924 records (32.6%) with rejected or added dates, and 743 records (26.2%) that contained several of the above problems: all these challenges have been handled (Fig. 2). After assessing initial age-depth models, accumulation rates were adjusted for 367 records (13.0%), and different section thicknesses were applied to 411 records (14.5%).

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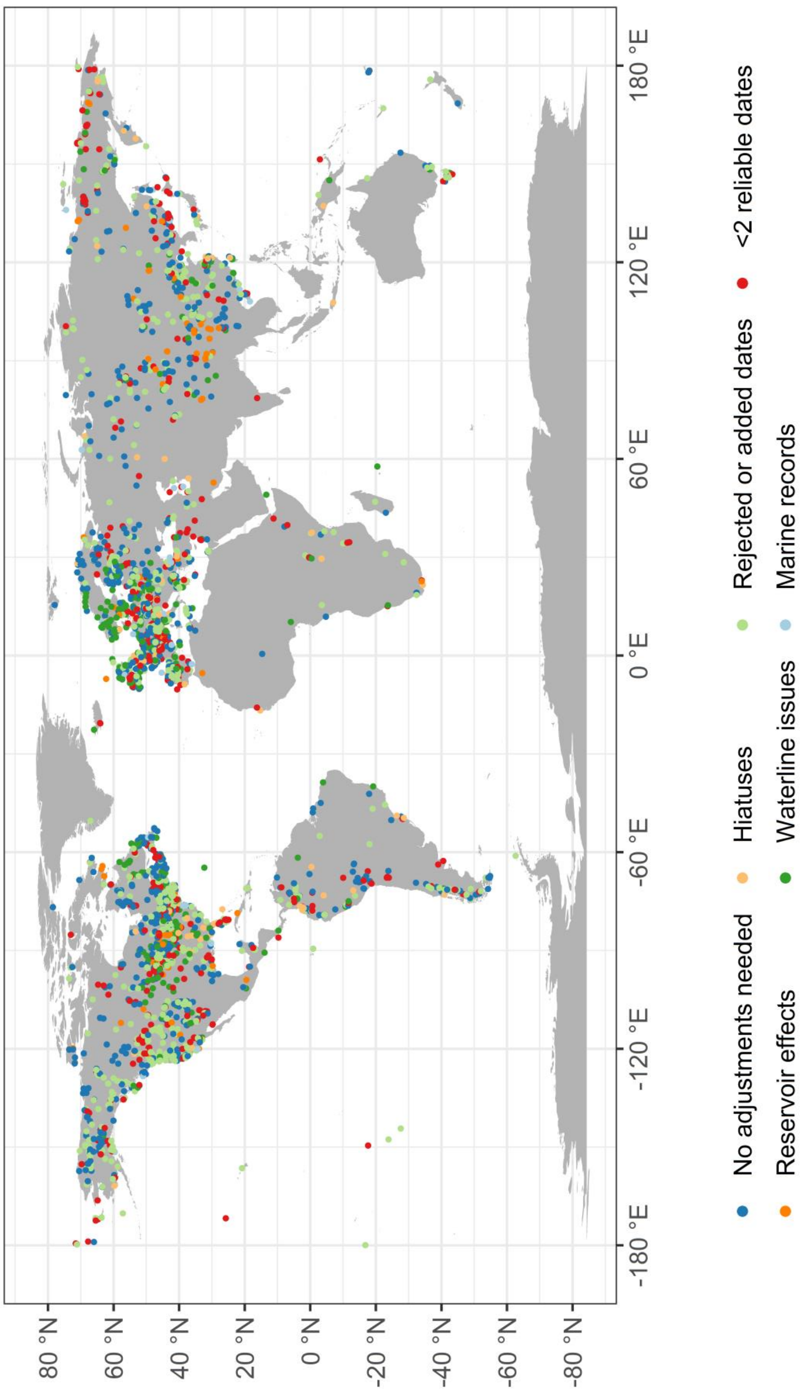

Figure 2. The distribution of records that faced various major challenges when establishing their chronologies.

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3.2 LegacyAge 1.0 quality

3.2.1 Dates used for final chronologies

A total of 19,990 control points (out of 21,199 dates available) were used to generate the chronologies for the 2831 records. Among them, the most common chronological control points are radiocarbon dates (86.1%), followed by lithological and biostratigraphical dates (8.5%) collected from publications or Neotoma, and lead-210 (5.0%); other dating techniques make up 0.4% of the control points. The median number of dates per chronology is 5, with 23.3% of the chronologies having 2 or 3 dates, 53.3% having 4-8 dates, and 23.4% having at least 9 dates (Fig. 3).

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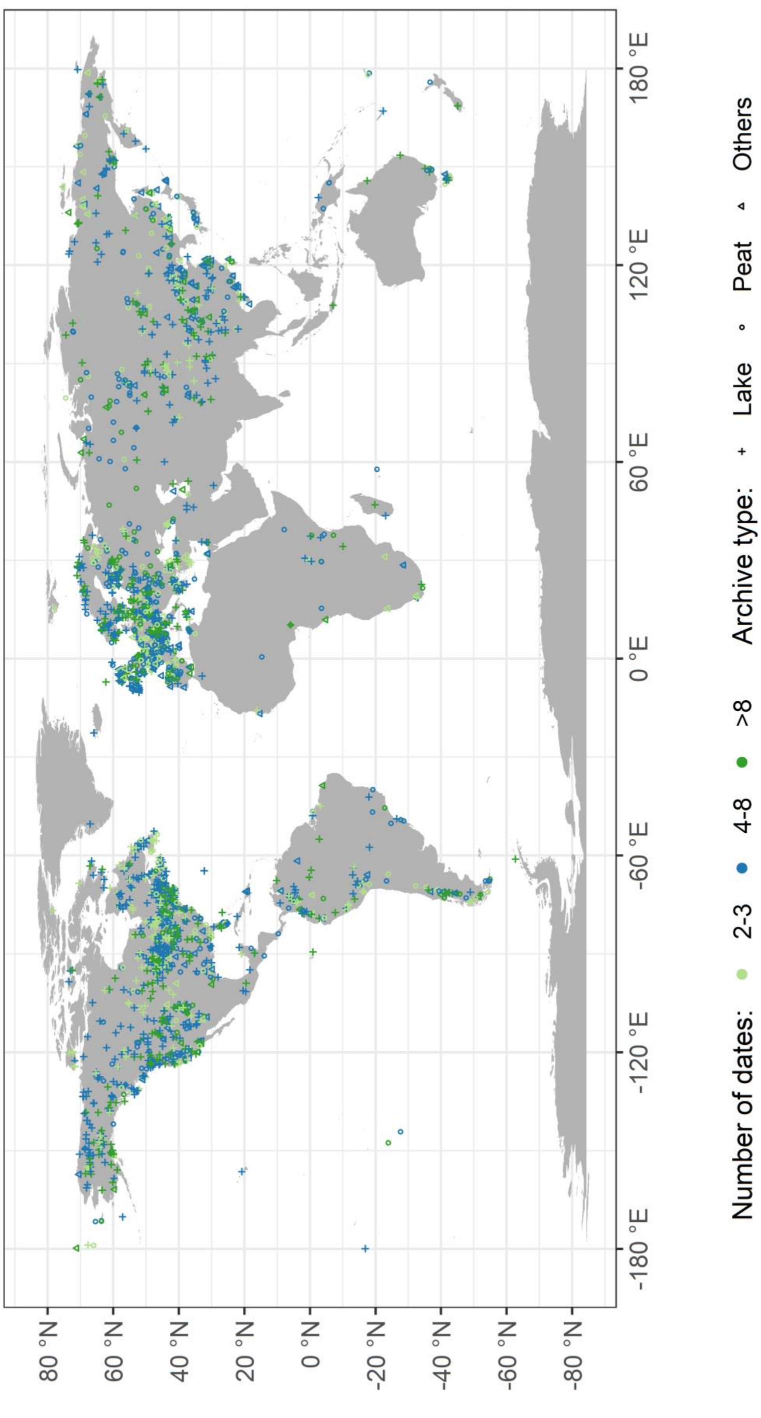

Figure 3. Map of the number of dates and archive types for each record.

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Currently, 80.5% of chronological control points in the LegacyAge 1.0 fall within the Holocene (37.9%, 25.8%, and 16.8% within the late (ca. 0-4.2 cal. ka BP), middle (ca. 4.2-8.3 cal. ka BP), and early Holocene (ca. 8.3-11.7 cal. ka BP), respectively), 14.5% within the Last Deglaciation (ca. 19.0-11.7 cal. ka BP; Clark et al., 2012), 2.0% within the Last Glacial Maximum (ca. 26.5-19.0 cal. ka BP; Clark et al., 2009), and only 3.0% earlier than the LGM (Fig. 4).

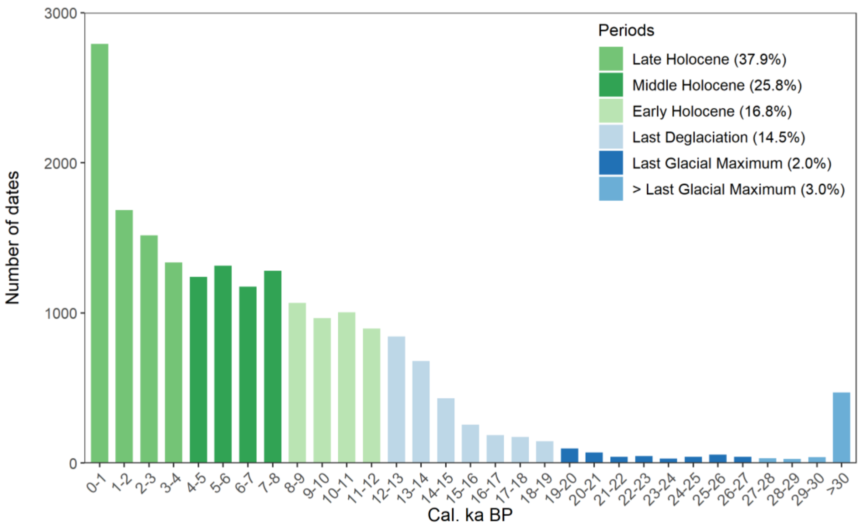

Figure 4. Histogram showing the number of available dates in distinct time slices.

3.2.2 Spatial and temporal coverage

Of the 2831 chronologies finally established, 1032 records are from North America, 1075 records from Europe, 488 records from Asia, 150 records from South America, 54 records from Africa, and 32 records from the Indo-Pacific (Fig. 3). Most records (2659 records, 93.9%) are in the northern hemisphere, where the main vegetation and climate zones are covered.

As shown in Fig. 5, 94.8% of chronologies cover part of the last 30 ka, while Marine Isotope Stage 3 (MIS-3) is relatively poorly covered. Specifically, 98.0% of chronologies cover part of the Holocene (90.7%, 81.0%, and 65.8% cover part of the late, middle, and early Holocene, respectively), 46.7% cover part of the Last Deglaciation, 10.7% cover part of the Last Glacial Maximum, and only 6.1% earlier than LGM.

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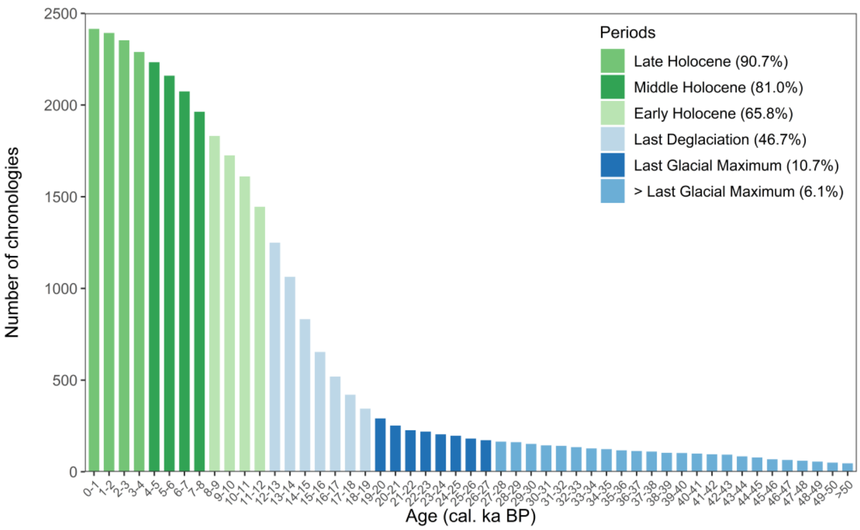

Figure 5. Histogram showing the number of available chronologies in distinct time slices.

3.2.3 Temporal uncertainty

Boxplots of age uncertainties for all chronologies in distinct time slices, excluding outliers (ca. 4.2%), illustrate that age uncertainty tends to increase with age and are mainly related to the uncertainties of the chronological control points and the uncertainty of the calibration curves (Fig. 6).

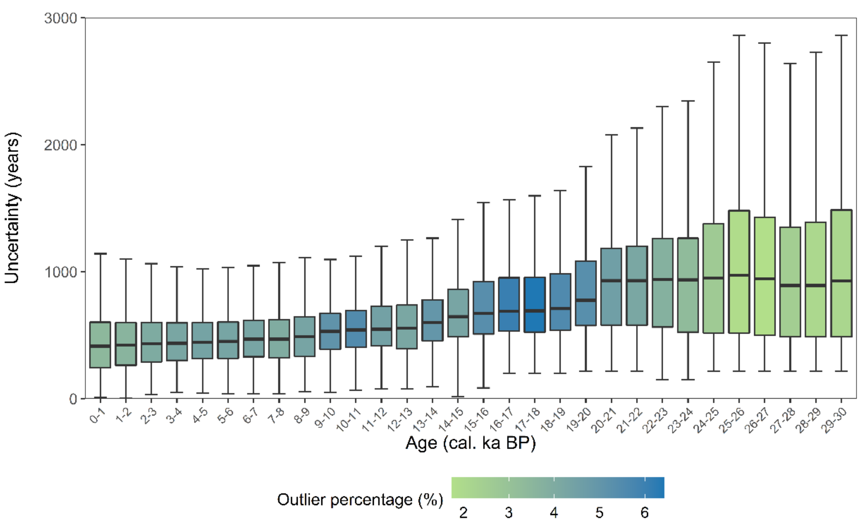

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Figure 6. Boxplots of age uncertainties and outlier percentages in distinct time slices.

3.3 Comparison of the LegacyAge 1.0 vs. original age-depth models

For 906 records out of the 2831 records included in the LegacyAge 1.0, no calibrated chronologies were originally available from the Neotoma and Cao et al. (2013, 2020) datasets for comparison. Of the remaining 1925 records, the new LegacyAge 1.0 chronologies were selected instead of the original ones in 95.4% of cases. Where original chronologies outperformed LegacyAge 1.0, it is mainly because they are varve chronologies, had incomplete metadata (e.g., missing sample depths), or they included some non-^{14}C dates that our model could not accommodate.

In most cases, the newly established chronologies were rather similar to the original ones. For 1012 records (52.6% of 1925 records), the original chronologies were within the 95% confidence intervals of the LegacyAge 1.0 chronologies, while the other 913 records (47.4%) were partially or completely outside the 95% confidence intervals.

Selected typical examples of the comparison results between the newly generated and original chronologies are illustrated in Fig. 7. For the *EL Tiro-Pass* record (ID 47502, Fig. 7a), both the original and newly generated chronologies were established by Bacon and are acceptable. However, our newly generated chronology has the advantage that it makes use of the latest radiocarbon calibration curve (IntCal20; Reimer et al., 2020), and the estimated surface age is more realistic as sediments are still accumulating (Niemann and Behling, 2008). For the *Fargher Pond* record (ID 15344, Fig. 7b), our newly generated chronology includes more varve ages from the Varved Sediments Database. These provide a better constraint for the lowermost profile than the original model had (Grigg and Whitlock, 2002). For the *Oltush Lake* record (ID 4320, Fig. 7c), the ^{14}C age of modern sediment in this lake is 350 yr BP and thus the assumption of a reservoir effect of 350 years resulted in slightly younger ages than originally given (Davydova and Servant-Vildary, 1996). Finally, for the *Soppensee* record (ID 44723, Fig. 7d), most of the ^{14}C dates (> 540 cm) have insufficient carbon (Hajdas and Michczyński, 2010) and thus the original chronology, generated from counting varves, outperformed our newly generated chronology.

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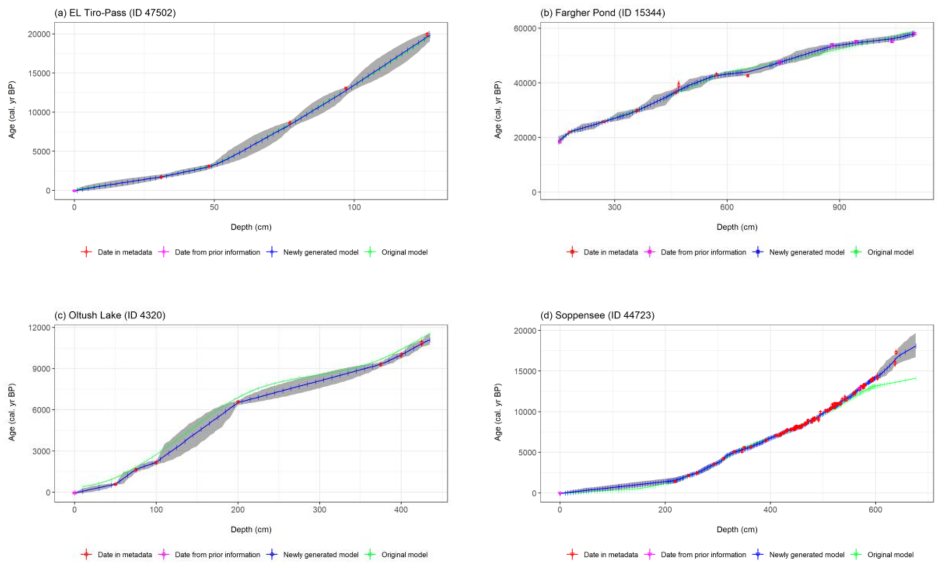

Figure 7. Comparison of newly generated age-depth models with the original ones.

4 Code and data availability

All data and R code used for this study are available at PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.933132; Li et al., 2021) and Github (https://github.com/LongtermEcology/ProxyAge-1.0), respectively.

5 Conclusion

This paper presents the framework as well as metadata, R pipeline, chronologies, and age uncertainties of 2831 pollen palynological records synthesized from the Neotoma Paleoecology Database (last access: April 2021) and 324 additional Asian records (Cao et al., 2013, 2020). Chronologies and uncertainties can be used from synthesis works; metadata and pipeline can be used to reestablish the chronologies for customized purposes, and the framework can be used for establishing chronologies for new records.

Author contributions. UH and CL designed the chronology dataset. CL and TB compiled the metadata and prior information of the chronologies. AP and TB wrote the R scripts and ran the analyses under the supervision of UH and CL. AD contributed an initial R script for creating age-depth models. CL wrote the first draft of the manuscript under the supervision of UH. All authors discussed the results and contributed to the final manuscript.

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

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