Geochronological database and classification system for age uncertainties in Neotropical Pollen records

Flantua, S.G.A.[1], Blaauw, M[2], Hooghiemstra, H.[1] and Data Contributors[3]

[1]{Research group of Palaeoecology and Landscape Ecology, Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, Science Park 904, 1098 XH Amsterdam, the Netherlands.}

[2]{School of Geography, Archaeology & Palaeoecology, Queen's University Belfast, UK}

[3] {Original depth files were provided by studies from the following data contributors (in alphabetic order): H. Behling, J-C. Berrío, C. Brunschön, A. Cleef, C. González-Arango, Z., González-Carranza, R.A.J. Grabandt, K. Graf, A. Gómez, W. Gosling, B.S.C., Hansen, K.F. Helmens, N. Jantz, P. Kuhry, B.W. Leyden, A. Melief, M.C. Moscol-Olivera, H. Niemann, F. Rodriguez, V. Rull, M.L. Salgado-Labouriau, J.B. Salomons, E.J. Schreve-Brinkman, D. Urrego, L.E. Urrego, T. Van der Hammen, C. Velásquez-Ruiz, M.I. Vélez, A. Villota, M. Wille, J.J. Williams.}

Correspondence to: S.G.A. Flantua (s.g.a.flantua@uva.nl)

Abstract

The newly updated inventory of palaeoecological research in Latin America offers an important overview of sites available for multi-proxy and multi-site purposes. From the collected literature supporting this inventory, we collected all available age model metadata to create a chronological database of 5116 control points (e.g. ^{14}C, tephra, fission track, OSL, ^{210}Pb) from 1097 pollen records. Based on this literature review, we present a summary of chronological dating and reporting in the Neotropics. Difficulties and recommendations for chronology reporting are discussed. Furthermore, for 228 pollen records in northwest South-America, a classification system for age uncertainties is implemented based on chronologies generated with updated calibration curves. With these outcomes age models are produced for those sites without an existing chronology, alternative age models are provided for researchers interested in comparing the effects of different calibration curves and age-depth modelling software, and the importance of uncertainty

assessments of chronologies is highlighted. Sample resolution and temporal uncertainty of ages are discussed for different time windows, focusing on events relevant for research on centennial to millennial-scale climate variability. All outcomes and developed R scripts are publically available.

Keywords

Geochronological Database - Latin American Pollen Database – Northwest South America – Temporal uncertainty assessment - Centennial-Millennial time-scale climate variability

1 Introduction

Temporal uncertainty remains a challenge in databases of fossil pollen records (Blois et al., 2011). The demands for precise and accurate chronologies have increased and so have the questions needing higher resolution data with accurate chronologies (Brauer et al., 2014). The increasing number of studies testing for potential synchronous patterns in paleo-proxies (Jennerjahn et al., 2004; Gajewski et al., 2006; Blaauw et al., 2007; Chambers et al., 2007; Blaauw et al., 2010; Giesecke et al., 2011; Austin et al., 2012) rely heavily on precise comparison between different records. Hypotheses have been proposed as to whether abrupt climatic changes were regionally and altitudinally synchronous, or whether there were significant ‘leads’ and ‘lags’ between and/or within the atmospheric, marine, terrestrial and cryospheric realms (Blockley et al., 2012). The popular ‘curve-matching’ of proxy data has been a cornerstone for correlating potential synchronous events, but this method neglects time-transgressive climate change (Blaauw, 2012; Lane et al., 2013). Thus, accurate age-depth modelling has been identified as crucial to derive conclusions on climate change signals from different paleo-archives (Seddon et al., 2014).

It is important to identify those few (but growing numbers of) records which have relatively precise chronological information (Blois et al., 2011; Seddon et al., 2014; Sundqvist et al., 2014). The development of large-scale analyses is relatively recent, demanding occasionally a different approach to data handling of individual pollen records. The latter were most often developed to explore questions on a local or regional terrain, by researchers unacquainted with requirements for multi-site integration. Multi-site temporal assessments have recently been presented for the European Pollen Database (EPD; Fyfe et al., 2009; Giesecke et al., 2014), for the African Pollen database (Hélyet al., 2014) and for the North American pollen database (Blois et al., 2011), but for Latin America this important assessment is still missing.

To support multi-site and multi-proxy comparison, collecting chronological information of pollen records and implementation of uncertainty assessments on their temporal spinal cords is an indispensable step. The recently updated inventory of palaeoecological studies in Latin America (Flantua et al., 2013; 2015a; Grimm et al., 2013) shows the vast amount of available palynological sites with potential geochronological data throughout the continent. Therefore, we created a geochronological database originating from the updated Latin American Pollen Database (LAPD) and corresponding literature database (1956-2014). Here we summarize the collected metadata on chronological dating and reporting in Neotropical studies. We describe the most commonly used dating methods, age modelling and calibration methods, and discuss fields of highest potential improvement in line with international recommendations. Furthermore, with the aim of enriching the discussion on uncertainty assessments of age models and exemplifying the use of geochronological data recollection, we produce age models from pollen records in northwest South-America (NW-SA). Updated calibration curves are used and we evaluate the temporal uncertainty of age models by a conceptual framework proposed by Giesecke et al. (2014) for ranking the quality of the chronologies as well as the individual ^{14}C ages and depths with pollen counts. Based on the combined temporal quality and resolution assessment, the time windows best suitable for inter-site and inter-proxy comparison are highlighted. The resulting chronologies are not assumed to be the best age models, but serve as alternative or potential age models for studies lacking published chronologies, reinforced by a temporal uncertainty assessment. We postulate that this study serves as a guidance to open up the discussion in South America on temporal quality of pollen records by providing a method openly accessible for adjustments and improvements. To stimulate reuse for new analyses and capacity building on age modelling, all outcomes and R scripts are available from data repositories.

2 Methods

2.1 Geochronological database of the Neotropics

To obtain an overview of the control points and age modelling methods used in pollen records throughout the region, we performed a thorough review of the LAPD and corresponding literature database (Flantua et al., 2015a). A total of 1245 publications were checked regarding their chronological information covering 1369 sites. For 270 sites only biostratigraphic dates were mentioned, no chronological details were provided, or the original publications with specifications were not found. These sites originate primarily from the 1970s and the 1980s, although even some recent publications lack details on the chronology. All other sites consisting of at least one chronological reference point enter the geochronological database at this stage (Fig. 1). The following chronology metadata was collected for each site: *Site Name*, *Year of Data Preparation, Age Model, Calibration Method, Software, Material Dated, Depth (min, max, mean), Thickness, Laboratory number, pMC (error),* ^{13}*C adjusted (± standard deviation),* ^{14}*C date (min, max, errors), Reservoir correction, Calibrated age (min, max, best age, errors), Additional relevant comments from authors.* Furthermore, all additional parameters needed to correctly reconstruct the chronologies, such as presence of hiatus, slumps, contaminated control points and other outliers identified by authors, were included. As a result, the Neotropical Geochronological Database (Neotrop-ChronDB) currently contains a total of 5116 chronological dates from 1097 sites throughout the study area.

2.2 Age model generation

From the Neotrop-ChronDB, all sites present in Venezuela, Colombia, Ecuador, Peru and Bolivia were extracted (Fig. 1, countries in grey). Over 300 publications were consulted to recalibrate control points and rebuild age models of 228 pollen records (see Supplement, Table S1). When more than one chronological date was available, new chronologies were generated with the updated calibration curves for the northern and the southern hemispheres, and maintained as closely as possible to the authors' interpretation of the age model. New chronologies were generated with updated calibration curves to a) be able to implement the temporal uncertainty analysis (the "star classification system"); b) to provide age models to studies without chronologies; c) to provide alternative age models for records based on older calibration curves or southern hemisphere records using the northern hemispheric calibration curves; d) to estimate the temporal resolution of pollen records in general and at specific time windows of interest in NW-SA.

Chronology control points

The most common control points are radiocarbon dates. For the age model generation we included the reported uncertainty of a date regardless of its origin (conventional or Accelerator Mass Spectrometry (AMS)). Additional important control points in constructing chronologies are ages derived from tephra

Biostratigraphic dates

For the generation of the recalibrated age models, stratigraphic dates were not used. Use of these layers would ignore the possibility that for example the palynologically-detectable onset of the Holocene was asynchronous throughout northern South America. Therefore any further inferences on spatial leads, lags or synchroneity would become flawed. Only in very few cases were very recent time markers used like the introduction of *Pinus.*

Core tops and basal ages: The non-‘decapitated’ top of the sediment sequence can be assigned to the year of sampling, if explicitly mentioned by the authors as the result of being the youngest sample in an undisturbed way. Frequently, however, assigning depths to core tops adds a factor of uncertainty because the uppermost sediments have not been consolidated and can be lost during coring. We did not use most of the estimated core tops as additional ages, but as with the bottom ages, let the recalibrated age model produce the new ages of the core tops. In case of considerable extrapolation or heavy overshooting of the age model (very young top ages), we produced alternative age models including the estimated top age. We decided to use the uncertainty range of ±50 yr considering that this standard deviation results in c. 300 yr of total uncertainty. We consider this value an appropriate estimate of uncertainty of core top ages. As the R-code of the procedures here presented is made available, researchers may adjust this value accordingly. Extrapolations from the new chronologies that went beyond -50 cal yr BP (years before AD 1950) were not used for the estimates on resolution.

Calibration curves

The South American continent covers the northern hemisphere (NH) as well as the southern hemisphere (SH). The previous SH calibration curve (SHCal04) only extended to 11 thousand calibrated years before present (here abbreviated as kcal BP). In age model tools like CLAM

(Blaauw, 2010), options were provided to “glue” the NH calibration curve to the SH curve to extend back to 50 kcal BP. However, recently the SH calibration curve was extended to 50 kcal BP (Hogg et al., 2013) and now obviates the need to use the NH curve for older dates in the SH. This provides new opportunities to recalibrate age models with updated calibration information and produce additional sample ages for re-evaluation. Nevertheless, tropical regions still face an uncertainty factor open to discussion, namely the southern limit of the Intertropical Convergence Zone (ITZC). McCormac et al. (2004) defined this limit to be the boundary between the NH and the SH, but models need additional data to better determine its exact location through time (McGee et al., 2014). For internal consistency we assigned the curve according to the general delimitation by Hogg et al. (2013) and Hua et al. (2013), or used the preferred calibration curve by the authors for the creation of the chronology. Mayle et al. (2000) for example, explicitly explain why their site in the Bolivian Amazonia experiences NH influences. Finally, a total of 22 sites include post-bomb dating for which 5 different regional curves options exist (Hua et al., 2013). Post-bomb calibration curves were as used by original authors or assigned according to Hua et al. (2013).

Age model methods

Depending on the number of available control points, two age-depth models were created per site. All age-depth relationships were reconstructed using the R-code CLAM version 2.2 (Blaauw, 2010; R Development Core Team, 2014), which is an R code for ‘classic age-modelling’ (Blaauw and Heegaard, 2012). The simplest age model, namely the *linear interpolation* method, produces a straightforward interpolation. It connects individual control points with straight lines which is in most cases unrealistic as it assumes abrupt changes in sedimentation rates at, and only at, the dated depths in the sediment core. The second age model method we used is the *smoothing spline*, with a default smoothing factor of 0.3. This interpolation method produces a curve between points that is also influenced by more distant control points. This method provides a smoother outline of age model and is considered to produce a more realistic model of the sedimentation process compared to the linear interpolation method. However, smoothing splines can only be modelled at sites that present 4 or more control points. Furthermore, age models were not run on cores that were problematic from the start. Examples are: cores where a hiatus/slump disrupts the age model in a way that no linear interpolation is possible; cores with many age reversals (when an older date lies above a younger date with limited dates collected); and cores with many nearly identical radiocarbon dates regardless of depth. Studies using tuning methods to establish their age models were not included.

Sample depths and ages

The sample depths were derived from either the raw dataset provided by the authors from the original paper or from the specifications and figures in the original publication. In a few cases, neither were available, so a 10-cm sample interval was assigned based on our assessments of the most likely depths for such dates. The sample age is obtained as the highest-probability age based on the distribution of estimated ages from 1000 Monte Carlo runs and the uncertainties are provided as 95 % confidence intervals.

Age model check

For each site, the newly produced models were evaluated and if necessary adjustments were made to deal with obvious outliers, 'overshooting' of the age model towards the top, and degree of 'smoothness' of the smooth spline model. Outliers were identified visually when control points deviated excessively from the general depth-age tendency. To solve over-extrapolation at the top (future dates), additional age models were created that included estimated surface dates. In some cases the default smoothing level of 0.3 was adjusted to 'touch' more of the available dates or to avoid an age reversal in the model. The most appropriate age model was selected in accordance to the authors' description, with a general preference for the smoothing spline model. With this model, we calculated the multi-site summary values, such as overall resolution and star classification system.

Data accessibility

The original data, the R-codes and the recalibrated age models from this paper are available through: http://dx.doi.org/xxx/xxx. We provide a manual that explains step by step the setup of the data and the use of the codes. For each individual pollen record, the corresponding folder contains the description of the original age model (copyright prevented the inclusion of pictures/figures), details on the recalibrated age models and the outcomes of the star classification system at sample level.

2.3 Temporal uncertainty estimates by the star classification system

We followed the age model evaluation proposed by Giesecke et al. (2014) to define the temporal quality and uncertainty of the chronologies and individual samples. An uncertainty classification based on assigning semi-quantitative "stars" focuses on the density of control point. The classification is additive and samples are assigned to the lowest class (a single star) where the estimated sample age is within 2000 years of the nearest control point. Additive stars are given at 1000-year and 500-year proximity to the nearest control point (Table 1). In addition to the three stars that characterize proximity to the nearest control point, an extra star is given to samples that are situated in a straight section of the sequence. The 'straightness' star is given to a sample where, within the nearest four control points, the modelled sediment accumulation rate changes less than 20%. Only sequences with at least four control points can obtain such an additional star. The evaluation is based on the position of the sample relative to the control points and is independent of the interpolation procedure. Therefore stars are assigned to the smooth spline output unless insufficient control points are available. The outcome of this classification produces a text file with the assigned number of stars for each sample along the core that is based on the depth file. The star classification is visualized along the vertical axis of the age model with coloured symbols (Fig 2).

2.4 Time window assessment

Rapid events of climate change occurred during the Dansgaard-Oescher (D-O) cycles spanning the last glacial cycle and during the Holocene. Recently published pollen records, like at Lake Titicaca, Bolivia (Fritz et al., 2010) and Lake Fúquene, Colombia (Groot et al., 2011) show clear evidence of millennial climate variability of large amplitude during Marine Isotope Stage (MIS) 4 to 2. As an example of the implementation of the star classification system, we select a series of consecutive time windows relevant for paleoclimate reconstructions at millennial time-scale. These time windows are: MIS 5 (c. 130-70 kcal BP), MIS 3 (c. 60-27 kcal BP; Van Meerbeeck et al., 2009), Heinrich event 1 (H1; c. 18-15 kcal BP; Álvarez-Solas et al., 2011), and the Younger Dryas (YD)/Holocene transition (c. 12,86 - 11,65 kcal BP; Rasmussen et al., 2006). For these time windows we summarize and discuss the temporal resolution and control-point density (the star classification system)

3 Results

3.1 Chronological data in the Neotropics

The number of available pollen records in this region has increased considerably in the last 20 years (Flantua et al., 2015a). During recent years, the number of control points used for stratigraphic age models has trended upwards; since 2010, the mean and median number of control points per published pollen site has been five and three, respectively (Flantua et al., 2015a). Here we provide more detail on the available chronologies, describing the most commonly used control points for dating, age modelling and calibration methods.

Radiocarbon dates

The Neotrop-ChronDB stores a total of 5,116 dates of which the most common control points are radiocarbon (^{14}C) dates. Radiocarbon dating has been used to date pollen records for more than five decades now. The first dated records in South America came from the Orinoco delta of Venezuela (Muller, 1959), and from Colombian sites such as Ciudad Universitaria, Laguna de la América, and Páramo de Palacio (Van der Hammen and González, 1960) and Laguna de Petenxil in Guatemala (Tsudaka, 1967). In the early stages of ^{14}C measurement, this technique required a minimal sample size of 0.5 g carbon (Povinec et al., 2009), while sample sizes differed greatly among materials (Bowman, 1990). In paleoecological research, this has always been a limiting factor as natural samples generally present a small $^{14}C/C$ ratio. As a consequence material to obtain a ^{14}C date sometimes originated from a wide depth interval of the sediment core. Consequently, conventional radiocarbon dating based on bulk samples of lake sediments is often a high-risk undertaking as it can result in a substantial uncertainty and puzzling date estimates.

The great breakthrough came from the development of AMS dating in 1977 that consisted of direct counting of the ^{14}C atoms present in a sample (Bowman, 1990; Povinec et al., 2009). This technique reduced the requirements for sample size and therefore improved the accuracy of samples. Furthermore, the required time to obtain dates was reduced from months to minutes. It took some time for AMS dating to appear in the Neotropics. It was not until the early 1990s that AMS dating was used in sites as Lake Miragoane, Haiti (Brenner and Binford, 1988), Laguna de Genovesa, Ecuador (Steinitz-Kannan et al., 1998) and Lake Quexil, Guatemala (Leyden et al., 1993). Ever since an increasing number of sites report AMS dates to support their chronologies with higher precision. Nevertheless, even in a recent record with AMS ages, authors have been struggling to compile a consistent age model due to low carbon content of the samples (Groot et al., 2014). The advantages of using ^{14}C as dating method, having broad applicability on many different sample materials and covering the most prevalent time range (50 kcal BP), surpasses other methods and therefore remains to be the most commonly applied scientific dating method.

Currently c. 68% of the geochronological dates in the LAPD fall within the last 10 kcal BP, 20% within 20-10 kcal BP and 4% within 30-20 kcal BP. A wide range of materials is used for dating: cellulose-containing materials (woods, seeds, achenes, plant remains, insect chitin; n=1,732); charcoal and charred material (n=191); carbonates (shells and calcite; n=118), collagen-containing materials (bones and coprolites; n=48); and bulk sediments from different materials (n=1,074).

Tephrochronometry

The terminology *Tephrochronology* means 'use of tephra layers as isochrons (time-parallel marker beds) to connect and synchronize sequences and to transfer relative or numerical ages to them using stratigraphy and other tools' (Lowe, 2011). The process of obtaining a numerical age or date for a tephra layer deposited after a volcanic eruption either directly or indirectly is called *Tephrochronometry* (Lowe, 2011). Primary minerals, such as zircon, K-feldspar and quartz, can be used to date tephras directly. Indirect methods include different applications such as radiometric dating (radiocarbon dating, fission-track dating, argon isotopes K/Ar, Ar/Ar, luminescence dating, U-series, $^{238}U/^{238}Th$ zircon dating) and incremental dating (annually banded found in the layering of ice cores) (Lowe, 2011). This field of advanced chronology is of essential importance in the search for precise dates for high-resolution paleoenvironmental records and research (Davies et al., 2012). Tephrochronology has become increasingly popular across a range of disciplines in the Quaternary field (Bronk Ramsey et al., 2015; Lowe, 2015), especially for linking and synchronizing paleorecords accurately along longer timescales. Several uncertainties in tephrochronology are similar to those known from radiocarbon dating such as methodological and dating errors, and reworking of dated layers. The specific challenges for this dating technique lay in that different tephras may display similar major element composition, or the same tephra may have a temporal and spatial compositional heterogeneity (see for a review and examples Lowe, 2011). International initiatives such as INTIMATE (http://intimate.nbi.ku.dk/) and INTREPID (Lowe, 2010) have aimed at improving uncertainties from tephrochronologies, supported by an expanding global database on tephra layers (http://www.tephrabase.org/). Although not extensive, we provide here an overview of studies that welcomed this technology to improve the chronologies of their pollen records.

From Mexico down to Patagonia, there are regions of elevated volcanic activities where frequent tephra layers can be found. Mexico's active seismic zones have numerous active volcanoes in the so-called 'Mexico's Volcanic Axis' or 'Trans-Mexican Volcanic Belt' (*Eje Volcánico Transversal*). Ortega-Guerrero and Newton (1998) collected tephra layers in southern Mexico specifically aimed to produce stratigraphic markers for palaeoenvironmental research. Tephra layers called Tlácuac, Tlapacoya and Toluco can be found in different pollen records such as Lake Texcoco (Lozano-García and Ortega-Guerrero, 1998) and Lake Chalco (Lozano-García et al., 1993). Additional tephra layers played an important role in the chronology of Lake Peten-Itza PI6, Guatemala (Hodell et al., 2008) and Laguna Llano del Espino and Laguna Verde, El Salvador (Dull, 2004a; 2004b).

The northern Andes forms part of the 'Northern Volcanic Zone' (Stern, 2004; Rodriguez-Vargas et al., 2005) and is shared by Colombia and Ecuador. In the Ruiz-Tolima region (Central Cordillera of Colombia), Herd (1982) identified 28 eruptive events during the last 14,000 years. Sites like Puente Largo and Llano Grande (Velásquez-R et al., 1999) make use of these events in their chronologies. Even sites along the Eastern Cordillera capture these volcanic ashes, like Funza (Andriessen et al., 1994; Torres et al., 2005) and El Abra (Kuhry et al., 1993), while the ridge itself lacks volcanic activities (Rodriguez-Vargas et al., 2005). Otoño-Manizales Enea (Cleef et al., 1995) reports 5 events between 44 and 28.5 thousand calendar years (kyr) BP and Fúquene another 6 events between 30 kyr and 21 kyr BP (Van Geel and Van der Hammen, 1973). Fission-track ages on sparse zircons were obtained for the long cores from Funza 1, Funza 2, Rio Frío and Facatativá (Andriessen et al., 1994; Wijninga, 1996).

Ecuador is also well known for its very active volcanic region. Two eruptions of the Guagua Pichincha and one of the Quilotoa were seen at pollen site Papallacta (Ledru et al., 2013). Thanks to four radiometric ^{40}Ar-^{39}Ar dates from tephra deposits, the chronology of the Erazo pollen record was placed within the middle Pleistocene period (Cardenas et al., 2011). An important overview of tephrochronology in southern Ecuador was provided by Rodbell et al. (2002).

The central Andes forms part of the 'Central Volcanic Zone' (Stern, 2004; Rodriguez-Vargas et al., 2005) and is shared by Peru and Bolivia. Several ice cores from the Sajama Ice Cap in Bolivia use ash layers from Volcán Huaynaputina in Peru as dating control (Reese, 2003). To support the chronology of the long core of Lake Titicaca, nine aragonite-rich layers for U/Th supported correlation with the last interglacial period (MIS5e; Fritz et al., 2007).

Finally, towards the south, the 'Southern Volcanic Zone' covers Chile and Argentina (Stern, 2004). An overview of the Holocene tephrochronology of this volcanic zone is presented in Naranjo and Stern (2004). The Pleistocene-Holocene transition has shown similarity in timing with an increase in volcanic activity in southern Chile (Abarzúa and Moreno, 2008). Jara and Moreno (2014) assessed the potential of volcanic events as being a driver of vegetation changes at a (sub-) millennial timescale based on 30 tephra layers since 13.5 kcal BP. Other sites with tephras to support their chronology are at Puerto del Hambre in Chile (Clapperton et al., 1995) and Rio Rubens in Argentina (Markgraf and Huber, 2010), among others.

Biostratigraphic dates

Before dating by ^{14}C became available and more affordable, many records relied on the identification of biostratigraphic zones. Biostratigraphy is a branch of stratigraphy based on the study of fossils (Traverse, 1988; Bardossy and Fodor, 2013). Delimitated zones were interpreted as sequences of rocks that are characterized by a specific assemblage of fossil remains (Gladenkov, 2010). Each zone is a reflection of changing paleoecological settings different from the previous zone, identified by a set of characteristics such as taxon composition or abundance, or phylogenetic lines (Gladenkov, 2010). In general, stratigraphic schemes are still subject to constant adjustments, being updated by new records, improved dating and taxonomic revision. Difficulties arise in the accurate delimitation of the boundaries of biostratigraphic zones. Furthermore, older records relied heavily on zonal matching without accurate chronological background and assuming synchronicity. Additionally, the zonation and biostratigraphy may depend on localized stratigraphic nomenclature and is sometimes not even directly applicable to adjacent areas. Finally, a biostratigraphic layer may have been defined using a sparse data set while depending heavily on correct taxonomy identification. Challenges of biostratigraphic correlation techniques are further explored in Punyasena et al. (2012) and Barossy and Fodor (2013).

Several biochronological schemes are used or under discussion in South America and describing their development (e.g. Van der Hammen, 1995; Van der Hammen and Hooghiemstra, 1995a) goes beyond the scope of this paper. Here we mention briefly some zones for NW-SA. Older records used presumably synchronous onsets of the Lateglacial as a reference point in time, such as numerous pollen records from the Valle de Lagunillas (González et al., 1966), Sierra Nevada (Van der Hammen, 1984) and Central Cordillera (Melief, 1985; Salomons, 1986). The transition of the Pleistocene/Holocene is often mentioned in diagrams, as is the YD. The onset of the Bølling/Allerød is less frequently used, whereas referring to and correlating regionally defined stadials and interstadials is more popular. For example, the ‘Guantiva interstadial’ (Van der Hammen and González, 1965; Van Geel and Van der Hammen, 1973) and ‘El Abra stadial’ (Kuhry et al., 1993; Van der Hammen and Hooghiemstra, 1995b) are commonly used biostratigraphic dates within Colombia. These periods are considered to be an equivalent to the North Atlantic Allerød Interstadial and the Younger Dryas sequence, respectively (van der Hammen and Hooghiemstra, 1995b). Similarly in the tropical Venezuelan Andes, the ‘Anteojos’ cold phase was proposed as equivalent to the cold reversal of the YD and in some aspects comparable to El Abra (Rull et al., 2010).

Other dating techniques

An exceptional dating method was used at Ciama 2 in Brazil, through Optically Stimulated Luminescence (OSL) encompassing the period between the MIS3 (MIS5 ages were discarded) and the last millennium (de Oliveira et al., 2012). The same technique was used at the Potrok Aike lake in Patagonia. A 65 kyr-long sediment core was recovered by the Potrok Aike Maar Lake Sediment Archive Drilling Project (PASADO; Recasens et al., 2012), where a combination of OSL, tephra and ^{14}C was used to establish its chronology (Buylaert et al., 2013; Recasens et al., 2015). The pollen record from this multi-proxy study is to be published soon and will be an important comparison to other long cores from South America regarding late Quaternary climate variability.

There are two important records that serve in South America as a key reference for regional chronology testing, which are Fúquene-9C (Groot et al., 2014) and the MD03-2622 marine core from the Cariaco basin (González et al., 2008). Both cores were analysed at high resolution (Fq-9C: 60 yr; Cariaco: 350 yr) and cover c. 284-27 kcal BP and 68-28 kcal BP, respectively. Both sites, however, implement different kinds of age models, namely frequency analyses of arboreal pollen % and orbital tuning (Fq-9C) and tuning to reflectance curve of another marine core (Cariaco, which itself has been tuned to Hulu Cave in China). Long records, such as also from lake Titicaca (LT01-2B and LT01-3A; Hanselman et al., 2005; Fritz et al., 2007; Gosling et al., 2008; Gosling et al., 2009; Hanselman et al., 2011), rely on advanced methods of orbital tuning for the older sections and are therefore not considered in this study for the recalibrated age model or star classification.

3.2 Reporting of ^{14}C measurements and corrections

Through the years the radiocarbon community has presented a series of papers indicating the proper way of reporting ^{14}C data (Stuiver and Polach, 1977; Mook and Van der Plicht, 1999; Reimer et al., 2004a). In the early days, the world's laboratories reported all of their produced radiocarbon dates in the journal *Radiocarbon*, a journal then dedicated to compiling these overviews. Probably the earliest radiocarbon dates from the Neotropics can be found in Vogel and Lerman (1969), describing in detail dates produced from Cuba, Jamaica, Colombia, Guyana, Surinam, Peru and Argentina. However, this system could not keep up with the increasing number of both laboratories and studies reporting radiocarbon dates. Since then the correct reporting of ^{14}C dates relied completely on the experience and willingness of the researchers.

Measured radiocarbon concentrations require an additional correction due to mass fractionation of ^{14}C atoms during natural bio-geochemical processes (e.g. photosynthesis; Drake, 2014), and sample preparation and measurement (Wigley and Muller, 1981). This is a $\delta^{13}C$-based correction which has a default value of -25‰ based on wood (Stuiver and Polach, 1977). In the Neotrop-ChronDB 1,283 ^{14}C dates have reported fractionation corrections ranging from -42 to 30.2‰, but it's not always clear if the authors implement any correction This number represents a quarter of the total number of radiocarbon dates in the database, meaning that over 600 studies do not report this fractionation correction.

Studies specifying additional corrections such as the possible reservoir age are rare. Although organic material potentially presents this ^{14}C offset, it is rarely identified in terrestrial pollen records in the area of interest. For the marine reservoir correction, the marine calibration curves incorporate a global ocean reservoir correction of c. 400 yr. Nevertheless, regional differences in reservoir values should be applied according to the Marine Calibration dataset (http://www.calib.qub.ac.uk/marine). Some marine studies in the region implemented a fixed reservoir effect of 400 yr (according to Bard, 1988) for marine dates, while others only mentioned the used version of the CALIB program. A handful of marine cores in Chile (MD07-3104; MD07-3107; MD07-3088) estimate different local reservoir ages on calibrated ages from the IntCal calibration curve.

While Stuiver and Polach (1977) were the first to establish the conventions for reporting radiocarbon data, Reimer et al. (2004b) dealt with the growing use of postbomb ^{14}C and a corresponding new symbol in ^{14}C reporting. Correct postbomb ^{14}C reporting is problematic in the Neotropics. Negative ^{14}C ages are treated highly variably, from being totally discharged, titled 'modern' or 'too young' without specified ^{14}C value, or considered valid as the subtracted age from 1950 AD (resulting in any age estimate between 2014 and 1950). Also postbomb dates as percentage modern carbon values (% pMC, normalized to 100%) or 'fraction of modern' (F14C, normalized to 1) sometimes mislead uninformed authors to be acceptable ^{14}C ages. At this moment, only one pollen record is known to report the F14C value with the corresponding postbomb curve as proposed by Reimer et al. (2004b), namely Quistococha in Peru (Roucoux et al., 2013). Laboratory sample or identification number (ID), which are given to the samples by the radiocarbon dating laboratory, enable the laboratory to be identified and should always be published alongside the ^{14}C measurements (Grimm et al., 2014; See the long version of the workshop report published at http://www.pages-igbp.org/calendar/127-pages/826-age-models-chronologies-and-databases).

3.3 Current age models and calibration curves

The relatively recent development of freely available computing packages has as a consequence that there is a large bulk in the Neotrop-ChronDB without any age model (n=457), where most radiocarbon dates are simply plotted along the pollen record without an explicit age-model. The most common age model (n=298) is based on the simplest design, namely the linear interpolation between the dated levels even though this is hardly a realistic reflection of the occurred sedimentation history (Bennett, 1994; Blaauw and Heegaard, 2012). Polynomial regression methods (n=31) and the smooth spline (n=12) are becoming increasingly popular but mostly in international peer-reviewed journals compared to national publications. In the latter linear interpolation is more persistent. In 6 cases, age models and calibrated ages were created by the authors without further explanation. In a significant number of cases, age-depth modelling was performed with uncalibrated ^{14}C ages, which does not produce valid results due to the non-linear relationship between radiocarbon years and calendar years.

The unclear geographical boundary between the NH and SH calibration curve has led to finding pollen records from the same region using curves from either side of the hemisphere. This is seen in the highland of Peru and Bolivia where the boundary between the IntCal13 (NH-curve) and SHCal13 (SH-curve) realms is still unclear and even causing the use of different calibration curves for the same lake. Several Bolivian lowland studies explain the influence of the southern range of the ITZC migration and therefore justify the use of the northern calibration curve (Mayle et al., 2000; Maezumi et al., 2015, this CP Special Issue). The existence of a ^{14}C age difference of up to a few decades between the northern and southern hemisphere has been discussed in the literature, e.g. McCormac et al. (1998), Turney & Palmer (2007) and Hogg et al. (2013). This temporal uncertainty should be taken into account and it would be useful if authors address the choice of calibration curve in the publications.

Statistical approaches to chronological modelling have expanded dramatically over the last two decades. Advances in computer processing power and methodology have now enabled Bayesian age models which require millions of data calculations – a method which would not have been possible before. The development of such freely available Bayesian age-modelling packages as ‘OxCal’ (Bronk Ramsey, 1995), ‘BCal’ (Buck et al., 1999), Bchron (Parnell et al. 2008), ‘BPeat’ (Blaauw and Christen, 2005) and ‘Bacon’ (Blaauw and Christen, 2011) has greatly advanced the science. To our knowledge, however, so far there has been only a single application of Bayesian methods for age modelling in South America, namely at Papallacta 1-08 (Ledru et al., 2013). The authors included *a priori* information on sedimentation rates and tephra-layers to construct the age model and consequently derive the best age for an uncertain tephra deposition. The use of the sedimentation conditions is a highly relevant component for age model development but rarely seen to be taken into account. Plotting the sediment record next to the age model would complement greatly the interpretation of the chronology (as shown as an example in Fig.2).

Combining prior information from the sequences with the geochronological data is the basis of a Bayesian approach to construct an age-depth model (Blaauw and Heegaard, 2012). The current lack of Bayesian based age models in the Neotropics could be due to classic age-depth models (based on linear interpolation, smooth splines or polynomial regressions) being regarded as the most realistic models, or to the usefulness of Bayesian methods not yet having been explored. Each model comes inherent with errors and uncertainties (Telford et al., 2004), and each method consists of different approaches to address them. Linear interpolation for example provides reasonable estimates for ages and the gradients between adjacent pairs of points, but only includes the errors at the individual age-determinations and does not consider uncertainties and additional measurements (Blaauw and Heegaard, 2012). A wider range of possible errors can be included in ‘mixed-effect models’, while Bayesian age-depth modelling produces more realistic estimates of ages and uncertainties. Although we did not engage into Bayesian modelling in this study, even if researchers find themselves without much prior knowledge of regional accumulation rates, Bayesian methods could well provide more realistic estimates of chronological uncertainties than classical methods (Blaauw et al., in prep). Researchers are encouraged to make use of the freely available character of the Bayesian software packages to test multiple age-depth models, compare models that best approximate their knowledge of the sediment conditions, and address these comparisons in their studies.

3.4 Age model evaluation of northwest South America (NW-SA)

From a total of 292 pollen records revised, 242 preliminary age models were regenerated based on the provided dates. The other 50 pollen records either presented a lack of multiple geochronological dates or had too many chronological problems. During the process of adjustments of the age models for hiatus, outliers, and slumps, another 9 pollen records were rejected as no reliable models could be produced. In 125 cases both linear interpolation and spline could be implemented, requiring at least 4 valid geochronological dates for the latter. The median number of stars for recalibrated chronologies of NW-SA is 3, which we consider surprisingly high.

Based on the 233 checked and recalibrated age models from NW-SA (see Supplement, Table S1), the sample resolution (maximum, minimum, median and mean value) was estimated per pollen site and for the entire NW-SA. The resolution was calculated as the time between two consecutive depths with proxy information (sample depths). Minimum resolutions range from 10 yr to 1 kyr, compared to the maximum value between 5 kyr and 36 kyr (mostly due to extrapolations). The overall sample resolution estimates indicate that the average temporal resolution of this multi-site synthesis is c. 240 yr, a resolution that allows analyses of ecological responses to sub-millennial-scale climate change. From a synoptic perspective, the NW-SA pollen records do not show spatial clustering based on the assigned stars (Fig. 3A). In other words, chronologies with good and poor control point density (number of control points per unit time) can be found along all the different elevational and latitudinal ranges. The best context to the star classification system can be given in conjunction with the sample resolution estimates as chronologies might present high sample resolution but poor chronological backup, and vice versa. What is evident as a result of the recalibrated age models is the high number of pollen records within the 0-500 yr resolution with relatively high temporal quality (Fig. 3B).

3.4 Time window evaluation

MIS 5 (c. 130-70 kcal BP): Within this study, this time window is represented by only 4 pollen records from two lakes, namely from lake Titicaca LT01-2B and LT01-3A (Hanselman et al., 2005; Fritz et al., 2007; Gosling et al., 2008; Gosling et al., 2009; Hanselman et al., 2011), Fúquene 3 and 7 (Mommersteeg, 1998; Van der Hammen and Hooghiemstra, 2003; Vélez et al., 2003; Bogotá-A et al., 2011). Research into millennial-scale climate variability is difficult during this time window, as sample resolution varies greatly from a few centuries to several millennia. For periods older than 65 kcal BP, mean resolution shifts around 2000 yr per sample with a star classification of mostly 0-1. Temporal uncertainty is high due to extrapolation of age models through limited number of control points and additional hiatus difficulties.

MIS 3 (60-27 kcal BP): MIS 3 is better represented in samples (Fig. 4A) and sites (Fig. 4B), and shows a wider variation in the star classification. The median number of 1 star still indicates a relatively poor control point density in the chronologies and therefore high temporal uncertainty.

This time window is characterized by relatively older sites with reduced chronological quality even though overall resolution is at centennial timescale (430 yr).

LGM, H1 and YD/Holocene transition: The vast majority of chronologies cover the Holocene and Lateglacial time intervals because they have been established from lakes formed after the last glaciation. Consistent with the large number of pollen records that reflect the Holocene (Flantua et al., 2015a), the highest density of palynological sampling covers the last 10 kcal (Fig.4C). Most samples fall within the category of presenting ‘good’ control point density, namely either 3 or 4, just as the individual sites evaluated (Fig.4D). There is an overall good point density in the NW-SA sites that cover the YD/Holocene transition but the Last Glacial Maximum (LGM) and H1 are represented by far fewer records with varying temporal quality.

The integration of the recalibrated chronologies and the estimated sample resolutions indicate the essential value of the existing radiocarbon calibration curves: There is a clear threshold at c. 55 kcal BP (beyond the extent of the current ^{14}C calibration curves) from where the control point density and resolution currently do not support research on millennial timescales, as sample resolutions are on average 1300 yr and temporal uncertainty high (Fig.5).

4 Discussion

4.1 Chronological data reporting

The relevance of publishing details on the sample, laboratory and reference numbers, provenance and reservoir correction details seems underestimated by authors in many cases. Studies with insufficient chronology reporting undermine the consistency and credibility of the results presented, and weaken the value of the radiocarbon dates. Furthermore, considering the expanding palynological research (Flantua et al., 2015a), papers with deviations in chronology reporting will most likely not be used within the context of multi-proxy comparisons or more expanded regional synthesis efforts. Additionally, paleo-vegetation records with proper chronology details are frequently scanned by the archaeological community to correlate human and environmental dynamics (Aceituno et al., 2013; Delgado et al., 2015). Equally relevant are paleoecological records with solid chronologies for late Pleistocene understanding of megafaunal extinctions (Barnosky et al., 2004). Missing out on the chronology description is without doubt an unnecessary way to affect the credibility and citation rate of any study. A top-down approach to improve radiocarbon reporting initiates at the journals demanding complete and correct chronology information. Not less important are the reviewers in critically evaluating the presented age models. Sources to remain updated on the requirements of dating reporting are numerous (e.g. see Millard, 2014), but specific details can be online accessed through http://www.c14dating.com/publication.html. Additional recommendations can be found in Blaauw and Heegaard (2012) and from the "Neotoma Age models, chronologies, and databases workshop" in Grimm et al. (2014).

4.2 Temporal uncertainty assessment of chronologies

The importance of high-resolution records but especially temporal quality has been illustrated through the development of updated age models and control point density assessments. Compared to the implementation of the method in the EPD (Giesecke et al., 2014), there is a higher proportion of samples and sites in the last 5 kcal BP in NW-SA. The most common sample resolution in the EPD is between 50 and 250 years, while the NW-SA has a mean resolution of 235 years. This resolution is actually higher than we expected and this could be due to several reasons. First of all, during the age modeling procedure, chronologies with too many disturbing features were not used, implementing a first selection towards the best possible age models. Secondly, to assign 10-cm sample intervals for older pollen records to unknown sample depths could be an overestimation for sample resolution (many older records were sampled at >20cm). Thirdly, there are several very high-resolution sites that cover significant time periods overpassing greatly in sample numbers the sites with relatively low temporal resolution. Any calculation based on multi-site information should use a median value instead of the mean value (Fig.3), which is less sensitive to extremes. Nonetheless, the general tendency is that pollen records in NW-SA are improving chronological settings with high sample resolution on centennial timescales.

Until now, differences in resolution and chronological quality between older and newer sites have hampered the ongoing discussion on the rapid climatic shifts such as the YD. A synchronous similar climate reversal at the YD is not evident throughout South America. Differences in magnitude have been observed between Venezuela and Colombia (Rull et al., 2010), while pollen records at relatively close distances in Peru/Bolivia are considered both different in timing and expression (Hansen, 1995; Paduano et al., 2003; Bush et al., 2005). This points again to the danger of using assumed synchronous events to align archives across a region, e.g., Israde-Alcántara et al. (2012a) who align several poorly dated sites in Latin America to circularly argue for a YD comet impact (Blaauw et al., 2012; Israde-Alcántara et al., 2012b). New studies on correlating biostratigraphic patterns with improved chronology are important as they can identify possible long-distance synchronicity of climate signals, but at the same time display their own local signature when supported by high-resolution data. Therefore, additional well-dated records have a high potential of contributing to this current discussion (e.g. Rull et al., 2010; Montoya et al., 2011). However, advanced tools to assess leads, lags and synchronocity in paleorecords are still urgently needed (Blockley et al., 2012; Seddon et al., 2014) while only few case studies have yet explored the available tools (Blaauw et al., 2007; Blaauw et al., 2010; Parnell et al. 2008). As long as the discussion consists of correlating poorly dated events, new hypotheses based on assumed synchronous events fail to provide additional insights to current questions.

5 Conclusions & Recommendations

This paper presents an overview on chronological dating and reporting in the Neotropics, based on a new Geochronological Database consisting of 5116 dates from 1097 pollen records. To support centennial to millennial scale climate research, the temporal resolution and quality of chronologies from 292 pollen records in the northwest South America were assessed based on the method proposed by Giesecke et al. (2014). This method includes associated evaluations of uncertainties for the inferred sample ages and age models, and is suitable for a wide range of proxies. Over 300 publications were evaluated and new age models were constructed based on new calibration curves implementing either linear interpolation or (preferentially) smoothing splines. Using the R-code CLAM these newly derived chronologies formed the basis to estimate the sample error from the uncertainties of control points density in the age model. These sample-age confidences are assigned so-called "stars" and this semi-quantitative star classification system is discussed for different time windows such as MIS5, MIS3, the LGM and the YD. Based on these classifications, uncertainties and age control requirement are discussed for research into millennium-scale climate variability. This provides a general-purpose chronology fit for most continental-scale questions and multi-proxy comparisons of temporal uncertainties.

Finally, we address specific fields of improvements for chronological reporting in pollen records. It is important for authors to report at the necessary detail the chronology of their sediment core because it is the spinal core of the interpretation. Furthermore, due to the spatial coverage of the

LAPD, for the increasing number of questions requiring multi-proxy comparison, sites can be selected based on their considered usefulness for models. There is a lose-lose situation by not including potentially important sites just because the chronology is insufficiently presented in the paper. The number of recent sites that present incomplete descriptions of their presumed age model is striking, leaving out information such as depths, calibration method, and even only presenting calibrated dates without further explanation.

The discussion on detecting synchronicity of rapid climate change events should pass from correlating chronologies with incompatible resolution and temporal quality, to understanding the causes of leads and lags between geographically different localities with high chronological settings. Future studies on detecting rapid climate changes in a multi-site and multi-proxy context can be supported in their site selection procedure by the method presented in Giesecke et al. (2014). The method here implemented is fully suitable for other regions and proxies that deal with geochronological dating. As the Neotrop-ChronDB currently covers a much larger area, similar exercises can be done for other regions.

The vast number of sites reflecting the last 10 kyr BP with high samples densities and well-presented chronologies offer great opportunities for currently running working groups, like the *International Biosphere Geosphere Programme / Past Global Change - 6k* (IGBP-Pages 6k, www.pages-igbp.org/workinggroups/landcover6k/intro) and *Long-Term climate REconstruction and Dynamics of South America – 2k* (LOTRED-SA-2k; www.pages-igbp.org/workinggroups/lotred-sa/intro). Both multi-proxy working groups address human–environmental interactions in which pollen records in Central and South America are a vital source of information (Flantua et al., 2015b).

The produced chronologies in this paper do not substitute the validity and interpretation of the authors' original chronology, but serve the purpose to present an overview of the current potential temporal resolution and quality, and contribute to the discussion on age model assessments. Data control often varies throughout the record, therefore we emphasize the recommendation provided by Giesecke et al. (2014) that the star classification should be used in conjunction with the propagation of age uncertainty from the dates through the age model. The success of the use of Bayesian methods depends partly on the background knowledge of the researchers (e.g. knowledge of accumulation rates of comparable sites in the region) to adjust the age model accordingly. As we do not pretend to have this *a priori* information to make full use of the results obtained from Bayesian modelling, we think it's more appropriate to motivate researchers to consider this method for future studies. Users should always check the original papers and address questions on the chronologies to the main authors. At the same time, calibration curves as well as age-modelling methods will continue to be updated, so age models should rather be considered as inherent to a dynamic process of continuous improvement, rather than a static side component of a paleoecological record. For that purpose, we would like to emphasize that there are increasingly more resources available for providing Digital Object Identifications (DOI) to stand-along datasets, figures and variable media to obtain the rights to be cited as any other literature reference (e.g. Fig Share: http://figshare.com; Data Dryad: http://datadryad.org/). Authors considering an updated version of an age model could evaluate these resources, as well as for unpublished pollen datasets.

Acknowledgements

This paper forms part of the INQUA International Focus Group, ACER (Abrupt Climate Changes and Environmental Responses) for Latin America (La-ACER; Urrego et al., 2014). We thank the Netherlands Organization for Scientific Research (NWO, grant 2012/13248/ALW) for financial support of this project. The Neotoma Paleoecology Database is supported by the Geoinformatics Program of the U.S. National Science Foundation, projects EAR-0947459 and EAR-0948652. PAGES co-supported both La-ACER workshops in Colombia (November 2012) and in Brazil (August 2013) (http://www.ephe-paleoclimat.com/acer/LaACER.htm). We would like to thank the editors for organizing the Special Issue "Millennial-scale variability in the American tropics and subtropics" and a special thanks to Dr. Dunia Urrego and Dr Mitchel J. Power for their encouragements and patience. We thank the reviewers Thomas Giesecke and Marie-Piere Ledru for their helpful advice on improving the manuscript. Last but not least, we are grateful to the researchers that provided us the depth files of the original pollen records for the purpose of this paper.

References

Abarzúa, A. M. and Moreno, P. I.: Changing fire regimes in the temperate rainforest region of southern Chile over the last 16,000 yr, Quat. Res., 69(1), 62–71, doi:10.1016/j.yqres. 2007.09.004, 2008.

Aceituno, F. J., Loaiza, N., Delgado-Burbano, M. E. and Barrientos, G.: The initial human settlement of northwest South America during the Pleistocene/Holocene transition: synthesis and perspectives, Quat. Int., 301, 23–33, doi:10.1016/j.quaint.2012.05.017, 2013.

Andriessen, P. A. M., Helmens, K. F., Hooghiemstra, H., Riezebos, P. A. and Van der Hammen, T.: Pliocene-Quaternary chronology of the sediments of the high plain of BogotÁ, Eastern Cordillera, Colombia, Quat. Sci. Rev., 12, 483–501, 1994.

Austin, W. E. N., Hibbert, F. D., Rasmussen, S. O., Peters, C., Abbott, P. M. and Bryant, C. L.: The synchronization of palaeoclimatic events in the North Atlantic region during Greenland Stadial 3 (ca 27.5 to 23.3 kyr b2k), Quat. Sci. Rev., 36, 154–163, doi:10.1016/j.quascirev. 2010.12.014, 2012.

Bard, E.: Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: paleoceanographic implications, Paleoceanography, 3(6), 635–645, doi:10.1029/PA003i006p00635, 1988.

Bardossy, G. and Fodor, J.: Evaluation of Uncertainties and Risks in Geology: New Mathematical Approaches for their Handling, Springer Science & Business Media., 2013.

Barnosky, A. D., Koch, P. L., Feranec, R. S., Wing, S. L. and Shabel, A. B.: Assessing the causes of late Pleistocene extinctions on the continents, Science, 306(5693), 70–75, doi:10.1126/science.1101476, 2004.

Bennett, K. D.: Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences, The Holocene, 4(4), 337–348, doi:10.1177/095968369400400401, 1994.

Björk, S.:Younger Drays oscillation, global evidence. In: Elias, S.A. (Eds.), Encyl. Quat. Sci. 4; Elsevier, Amsterdam, 1985-1993, 2007.

Blaauw, M.: Methods and code for "classical" age-modelling of radiocarbon sequences, Quat. Geochronol., 5(5), 512–518, doi:10.1016/j.quageo.2010.01.002, 2010.

Blaauw, M.: Out of tune: the dangers of aligning proxy archives, Quat. Sci. Rev., 36, 38–49, doi:10.1016/j.quascirev.2010.11.012, 2012.

Blaauw, M., Christen, J.A., 2005. Radiocarbon peat chronologies and environmental change. J. R. Stat. Soc. Ser. C Appl. 54, 805–816. doi:10.1111/j.1467-9876.2005.00516.x

Blaauw, M. and Christen, J. A.: Flexible paleoclimate age-depth models using an autoregressive gamma process, Bayesian Anal., 6(3), 457–474, doi:10.1214/ba/1339616472, 2011.

Blaauw, M., Christen, J. A., Mauquoy, D., Van der Plicht, J. and Bennett, K. D.: Testing the timing of radiocarbon-dated events between proxy archives, The Holocene, 17(2), 283–288, doi:10.1177/0959683607075857, 2007.

Blaauw, M. and Heegaard, E.: Estimation of age-depth relationships, in: Birks, H.J.B., Lotter, A.F., Juggins, S., Smol, J.P. (Eds.), Tracking environmental change using lake sediments, Developments in Paleoenvironmental Research Vol. 5: Data handling and statistical techniques, Springer, Dordrecht, The Netherlands, 379–413, 2012.

Blaauw, M., Holliday, V. T., Gill, J. L. and Nicoll, K.: Age models and the Younger Dryas impact hypothesis, Proc. Natl. Acad. Sci., 109(34), 2240, doi:10.1073/pnas.1206143109, 2012.

Blaauw, M., Wohlfarth, B., Christen, J. A., Ampel, L., Veres, D., Hughen, K. A., Preusser, F. and Svensson, A.: Were last glacial climate events simultaneous between Greenland and France? A quantitative comparison using non-tuned chronologies, J. Quat. Sci., 25(3), 387–394, doi:10.1002/jqs.1330, 2010.

Blockley, S. P. E., Lane, C. S., Turney, C. S. M. and Bronk Ramsey, C.: The INTegration of Ice core, MArine and TErrestrial records of the last termination (INTIMATE) 60,000 to 8000 BP, Quat. Sci. Rev., 36, 1, doi:10.1016/j.quascirev.2011.10.001, 2012.

Blois, J. L., Williams, J. W., Grimm, E. C., Jackson, S. T. and Graham, R. W.: A methodological framework for assessing and reducing temporal uncertainty in paleovegetation mapping from late-Quaternary pollen records, Quat. Sci. Rev., 30(15-16), 1926–1939, doi:10.1016/j.quascirev. 2011.04.017, 2011.

Bogotá-A, R. G., Groot, M. H. M., Hooghiemstra, H., Lourens, L. J., Van der Linden, M. and Berrio, J. C.: Rapid climate change from north Andean Lake Fúquene pollen records driven by obliquity: implications for a basin-wide biostratigraphic zonation for the last 284 ka, Quat. Sci. Rev., 30(23-24), 3321–3337, doi:10.1016/j.quascirev.2011.08.003, 2011.

Bowman, S. (Ed.): Radiocarbon dating. University of California Press/British Museum, Berkeley and Los Angeles, USA, 64 pp., 1990.

Brauer, A., Hajdas, I., Blockley, S. P. E., Bronk Ramsey, C., Christl, M., Ivy-Ochs, S., Moseley, G. E., Nowaczyk, N. N., Rasmussen, S. O., Roberts, H. M., Spötl, C., Staff, R. A. and Svensson, A.: The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval, Quat. Sci. Rev., 106, 47-66, doi:10.1016/j.quascirev.2014.07.006, 2014.

Brenner, M. and Binford, M. W.: A sedimentary record of human disturbance from Lake Miragoane, Haiti, J. Paleolimnol., 1(2), 85–97, 1988.

Bronk Ramsey, C.: Radiocarbon calibration and analyses of stratigraphy: the OxCal Program, Radiocarbon, 37(2), 425–430, 1995.

Bronk Ramsey, C., Housley, R. A., Lane, C. S., Smith, V. C. and Pollard, A. M.: The RESET tephra database and associated analytical tools, Quat. Sci. Rev., 118, 33-47, doi:10.1016/j.quascirev. 2014.11.008, 2015.

Buck, C.E., Christen, J.A. and James, G.N.: BCal: An on-line Bayesian radiocarbon calibration tool. Internet Archaeol. 7, http://intarch.ac.uk/journal/issue7/ buck/, last accessed January 2015, 1999.

Bush, M. B., Hansen, B. C. S., Rodbell, D. T., Seltzer, G. O., Young, K. R., León, B., Abbott, M. B., Silman, M. R. and Gosling, W. D.: A 17,000-year history of Andean climate and vegetation change from Laguna de Chochos, Peru, J. Quat. Sci., 20(7-8), 703–714, doi:10.1002/jqs.983, 2005.

Buylaert, J.-P., Murray, A. S., Gebhardt, A. C., Sohbati, R., Ohlendorf, C., Thiel, C., Wastegård, S. and Zolitschka, B.: Luminescence dating of the PASADO core 5022-1D from Laguna Potrok Aike (Argentina) using IRSL signals from feldspar, Quat. Sci. Rev., 71, 70–80, doi:10.1016/j.quascirev.2013.03.018, 2013.

Cardenas, M. L., Gosling, W. D., Sherlock, S. C., Poole, I., Pennington, R. T. and Mothes, P.: The response of vegetation on the Andean flank in western Amazonia to Pleistocene climate change, Science, 331(6020), 1055–1058, doi:10.1126/science.1197947, 2011.

Chambers, F. M., Mauquoy, D., Brain, S. A., Blaauw, M. and Daniell, J. R. G.: Globally synchronous climate change 2800 years ago: Proxy data from peat in South America, Earth Planet. Sci. Lett., 253(3–4), 439–444, doi:10.1016/j.epsl.2006.11.007, 2007.

Clapperton, C. M., Sugden, D. E., Kaufman, D. S. and McCulloch, R. D.: The last glaciation in central Magellan Strait, southernmost Chile, Quat. Res., 44, 133–148, 1995.

Cleef, A. M., Noldus, G. W. and Van der Hammen, T.: Estudio palinologico del Pleniglacial Medio de la sección Rio Otoño-Manizales Enea (Cordillera Central, Colombia), in: Van der Hammen, T. and A. G. dos Santos (Eds.) : Studies on Tropical Andean Ecosystems/Estudios de Ecosistemas Tropandinos 4, Cramer (Borntraeger), Berlin/Stuttgart, Germany, 441–449, 1995.

Davies, S. M., Abbott, P. M., Pearce, N. J. G., Wastegård, S. and Blockley, S. P. E.: Integrating the INTIMATE records using tephrochronology: rising to the challenge, Quat. Sci. Rev., 36, 11–27, doi:10.1016/j.quascirev.2011.04.005, 2012.

Delgado, M., Aceituno, F. J. and Barrientos, G.: ^{14}C data and the early colonization of northwest South America: a critical assessment, Quat. Int., 363, 55-64, doi:10.1016/j.quaint.2014.09.011, 2015.

Drake, B. L.: Using models of carbon isotope fractionation during photosynthesis to understand the natural fractionation ratio, Radiocarbon, 56(1), 29–38, doi:10.2458/56.16155, 2014.

Dull, R. A.: A Holocene record of Neotropical savanna dynamics from El Salvador, J. Paleolimnol., 32(3), 219–231, 2004a.

Dull, R. A.: An 8000-year record of vegetation, climate, and human disturbance from the Sierra de Apaneca, El Salvador, Quat. Res., 61(2), 159–167, doi:10.1016/j.yqres.2004.01.002, 2004b.

Flantua, S. G. A., Hooghiemstra, H., Grimm, E. C. and Markgraf, V.: Updated Latin American Pollen Database: Version 2013 in preparation for Neotoma, PAGES News, 21(2), 88, 2013.

Flantua, S. G. A., Hooghiemstra, H., Grimm, E. C., Behling, H., Bush, M. B., González-Arango, C., Gosling, W. D., Ledru, M. P., Lozano-García, S., Maldonado, A., Prieto, A. R., Rull, V. and Van Boxel, J. H.: Updated site compilation of the Latin American Pollen Database, Rev. Palaeobot. Palynol., http://dx.dpo.org/10.1016/j .revpalbo.2015.09.008, 2015a.

Flantua, S. G. A., Hooghiemstra, H., Vuille, M., Behling, H., Carson, J. F., Gosling, W. D., Hoyos, I., Ledru, M. P., Montoya, E., Mayle, F., Maldonado, A., Rull, V., Tonello, M. S., Whitney, B. S. and González-Arango, C.: Climate variability and human impact on the environment in South America during the last 2000 years: synthesis and perspectives, Climate of the Past Discussions, 11(4), 3475–3565, doi:10.5194/cpd-11-3475-2015, 2015b.

Fritz, S. C., Baker, P. A., Ekdahl, E., Seltzer, G. O. and Stevens, L. R.: Millennial-scale climate variability during the Last Glacial period in the tropical Andes, Quat. Sci. Rev., 29(7-8), 1017–1024, doi:10.1016/j.quascirev.2010.01.001, 2010.

Fritz, S. C., Baker, P. A., Seltzer, G. O., Ballantyne, A., Tapia, P., Cheng, H. and Edwards, R. L.: Quaternary glaciation and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project, Quat. Res., 68(3), 410–420, doi:10.1016/j.yqres.2007 .07.008, 2007.

Fyfe, R. M., Beaulieu, J.-L. de, Binney, H., Bradshaw, R. H. W., Brewer, S., Flao, A. L., 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, Veg. Hist. Archaeobot., 18(5), 417–424, doi:10.1007/s00334-009-0215-9, 2009.

Gajewski, K., Viau, A. E., Sawada, M., Atkinson, D. E. and Fines, P.: Synchronicity in climate and vegetation transitions between Europe and North America during the Holocene, Clim. Change, 78(2-4), 341–361, doi:10.1007/s10584-006-9048-z, 2006.

Giesecke, T., Bennett, K. D., Birks, H. J. B., Bjune, A. E., Bozilova, E., Feurdean, A., Finsinger, W., Froyd, C., Pokorný, P., Rösch, M., Seppä, H., Tonkov, S., Valsecchi, V. and Wolters, S.: The pace of Holocene vegetation change – testing for synchronous developments, Quat. Sci. Rev., 30(19-20), 2805–2814, doi:10.1016/j.quascirev.2011.06.014, 2011.

Giesecke, T., Davis, B., Brewer, S., Finsinger, W., Wolters, S., Blaauw, M., Beaulieu, J.-L. de, Binney, H., Fyfe, R. M., Gaillard, M.-J., Gil-Romera, G., Van der Knaap, W. O., Kuneš, P., Kühl, N., van Leeuwen, J. F. N., Leydet, M., Lotter, A. F., Ortu, E., Semmler, M. and Bradshaw, R. H. W.: Towards mapping the late Quaternary vegetation change of Europe, Veg. Hist. Archaeobot., (23(1), 75-86, doi:10.1007/s00334-012-0390-y, 2014.

González, E., Van der Hammen, T. and Flint, R. F.: Late Quaternary glacial and vegetational sequence in Valle de Lagunillas, Sierra Nevada del Cocuy, Colombia, Leidse Geol. Meded., 32, 157–182, 1966.

González, C., Dupont, L. M., Behling, H. and Wefer, G.: Neotropical vegetation response to rapid climate changes during the last glacial period: Palynological evidence from the Cariaco Basin, Quat. Res., 69(2), 217–230, doi:10.1016/j.yqres.2007.12.001, 2008.

Gosling, W. D., Bush, M. B., Hanselman, J. A. and Chepstow-Lusty, A.: Glacial-interglacial changes in moisture balance and the impact on vegetation in the southern hemisphere tropical Andes (Bolivia/Peru), Palaeogeogr. Palaeoclimatol. Palaeoecol., 259(1), 35–50, doi:10.1016/j.palaeo.2007.02.050, 2008.

Gosling, W. D., Hanselman, J. A., Knox, C., Valencia, B. G. and Bush, M. B.: Long-term drivers of change in *Polylepis* woodland distribution in the central Andes, J. Veg. Sci., 20(6), 1041–1052, doi:10.1111/j.1654-1103.2009.01102.x, 2009.

Grimm, E. C., Blaauw, M., Buck, C. E. and Williams, J. W.: Age models, chronologies, and databases workshop, PAGES Mag., 22(2), 104, 2014. http://www.pages-igbp.org/calendar/127-pages/826-age-models-chronologies-and-databases

Grimm, E. C., Bradshaw, R. H. W., Brewer, S., Flantua, S., Giesecke, T., Lézine, A.-M., Takahara, H. and Williams, J. W.: Pollen methods and studies | Databases and their application, in: Elias, S.A. (Ed.), Encycl. Quat. Sci. (Second Edition), Elsevier, Amsterdam, 831–838, 2013.

Groot, M. H. M., Bogotá, R. G., Lourens, L. J., Hooghiemstra, H., Vriend, M., Berrio, J. C., Tuenter, E., Van der Plicht, J., Van Geel, B., Ziegler, M., Weber, S. L., Betancourt, A., Contreras, L., Gaviria, S., Giraldo, C., González, N., Jansen, J. H. F., Konert, M., Ortega, D., Rangel, O., Sarmiento, G., Vandenberghe, J., Van der Hammen, T., Van der Linden, M. and Westerhoff, W.: Ultra-high resolution pollen record from the northern Andes reveals rapid shifts in montane climates within the last two glacial cycles, Clim. Past, 7(1), 299–316, doi:10.5194/cp-7-299-2011, 2011.

Groot, M. H. M., Van der Plicht, J., Hooghiemstra, H., Lourens, L. J. and Rowe, H. D.: Age modelling for Pleistocene lake sediments: A comparison of methods from the Andean Fúquene basin (Colombia) case study, Quat. Geochronol., 22, 144–154, doi:10.1016/j.quageo. 2014.01.002, 2014.

Hanselman, J. A., Bush, M. B., Gosling, W. D., Collins, A., Knox, C., Baker, P. A. and Fritz, S. C.: A 370,000-year record of vegetation and fire history around Lake Titicaca (Bolivia/Peru), Palaeogeogr. Palaeoclimatol. Palaeoecol., 305(1-4), 201–214, doi:10.1016/j.palaeo.2011.03.002, 2011.

Hanselman, J. A., Gosling, W. D., Paduano, G. M. and Bush, M. B.: Contrasting pollen histories of MIS 5e and the Holocene from Lake Titicaca (Bolivia/Peru), J. Quat. Sci., 20(7-8), 663–670, doi:10.1002/jqs.979, 2005.

Hansen, B. C.: A review of lateglacial pollen records from Ecuador and Peru with reference to the Younger Dryas event, Quat. Sci. Rev., 14, 853–865, 1995.

Herd, D. G.: Glacial and volcanic geology of the Ruiz-Tolima volcanic complex Cordillera Central, Colombia, INGEOMINAS, Bogotá, Colombia, 48 pp, 1982.

Hodell, D. A., Anselmetti, F. S., Ariztegui, D., Brenner, M., Curtis, J. H., Gilli, A., Grzesik, D. A., Guilderson, T. J., Müller, A. D. and Bush, M. B.: An 85-ka record of climate change in lowland Central America, Quat. Sci. Rev., 27(11-12), 1152–1165, doi:10.1016/j.quascirev. 2008.02.008, 2008.

Hogg, A. G., Hua, Q., Blackwell, P. G., Niu, M., Buck, C. E., Guilderson, T. P., Heaton, T. J., Palmer, J. G., Reimer, P. J., Reimer, R. W., Turney, C.S.M., Zimmerman, S.R.H.: SHCal13 Southern Hemisphere calibration, 0–50,000 cal yr BP, Radiocarbon, 55(4), 1889-1903, 2013.

Hua, Q., Barbetti, M. and Rakowski, A. Z.: Atmospheric radiocarbon for the period 1950–2010, Radiocarbon, 55(4), 2059–2072, 2013.

Israde-Alcántara, I., Bischoff, J.L., Domínguez-Vázquez, G., Li, H.-C., DeCarli, P.S., Bunch, T.E., Wittke, J.H., Weaver, J.C., Firestone, R.B., West, A., Kennett, J.P., Mercer, C., Xie, S., Richman, E.K., Kinzie, C.R., Wolbach, W.S., 2012a. Evidence from central Mexico supporting the Younger Dryas extraterrestrial impact hypothesis. Proc. Natl. Acad. Sci., a 109, 738–747. doi:10.1073/pnas.1110614109

Israde-Alcántara, I., Bischoff, J.L., DeCarli, P.S., Domínguez-Vázquez, G., Bunch, T.E., Firestone, R.B., Kennett, J.P., West, A., 2012b. Reply to Blaauw et al., Boslough, Daulton, Gill et al., and

Hardiman et al.: Younger Dryas impact proxies in Lake Cuitzeo, Mexico. Proc. Natl. Acad. Sci. 109, 2245–2247. doi:10.1073/pnas.1209463109

Jara, I. A. and Moreno, P. I.: Climatic and disturbance influences on the temperate rainforests of northwestern Patagonia (40 °S) since ∼14,500 cal yr BP, Quat. Sci. Rev., 90, 217–228, doi:10.1016/j.quascirev.2014.01.024, 2014.

Jennerjahn, T. C., Ittekkot, V., Arz, H. W., Behling, H., Pätzold, J. and Wefer, G.: Asynchronous terrestrial and marine signals of climate change during Heinrich events, Science, 306(5705), 2236–2239, doi:10.1126/science.1102490, 2004.

Kuhry, P., Hooghiemstra, H., Van Geel, B. and Van der Hammen, T.: The El Abra stadial in the Eastern Cordillera of Colombia (South America), Quat. Sci. Rev., 12(5), 333–343, 1993.

Lane, C. S., Brauer, A., Blockley, S. P. E. and Dulski, P.: Volcanic ash reveals time-transgressive abrupt climate change during the Younger Dryas, Geology, 41(12), 1251–1254, doi:10.1130/G34867.1, 2013.

Ledru, M.-P., Jomelli, V., Samaniego, P., Vuille, M., Hidalgo, S., Herrera, M. and Ceron, C.: The Medieval climate anomaly and the Little Ice age in the eastern Ecuadorian Andes, Clim. Past, 9(1), 307–321, doi:10.5194/cp-9-307-2013, 2013.

Leyden, B.W., Brenner, M., Hodell, D.A., Curtis, J.H., 1993. Late Pleistocene climate in the central American lowlands, in: Swar, P.K. (Ed.), American Geophysical Union, Washington, D.C., pp. 165–178.

Lowe, D.J.: Uncertainty in tephrochronology. SUPRAnet consortium workshop ‘Studying uncertainty in palaeoclimate reconstruction’, Sheffield, U.K., 23-27 June 2008. Available from: http://caitlinbuck.staff.shef.ac.uk/SUPRAnet/ (Accessed September 2015), 2008.

Lowe, D. J.: Project 0907: INTREPID – Enhancing tephrochronology as a global research tool through improved fingerprinting and correlation techniques and uncertainty modelling, University of Waikato Research Commons [online] Available from: http://researchcommons.waikato.ac.nz/handle/10289/4183 (Accessed 9 October 2015), 2010.

Lowe, D. J.: Tephrochronology and its application: a review, Quat. Geochronol., 6(2), 107–153, doi:10.1016/j.quageo.2010.08.003, 2011.

Lowe, D. J.: Connecting and dating with tephras: principles, functioning, and application of tephrochronology in Quaternary research, Conference: 12th Quaternary Techniques Short Course "Techniques of Palaeoclimatic and Palaeoenvironmental Reconstruction" (21-22 May, 2015), At National Isotope Centre, GNS Science, Lower Hutt, New Zealand, [online] Available from: http://researchcommons.waikato.ac.nz/handle/10289/9338 (Accessed 10 July 2015), 2015.

Lozano-García, M. S. and Ortega-Guerrero, B.: Late Quaternary environmental changes of the central part of the Basin of Mexico; correlation between Texcoco and Chalco basins, Rev. Palaeobot. Palynol., 99, 77–93, 1998.

Lozano-García, M. S., Ortega-Guerrero, B., Caballero-Miranda, M. and Urrutia-Fucugauchi, J.: Late Pleistocene and Holocene paleoenvironments of Chalco Lake, Central Mexico, Quat. Res., 40(3), 332–342, doi:10.1006/qres.1993.1086, 1993.

Maezumi, S. Y., Power, M. J., Mayle, F. E., McLauchlan, K. and Iriarte, J.: The effects of past climate variability on fire and vegetation in the cerrãdo savanna ecosystem of the Huanchaca Mesetta, Noel Kempff Mercado National Park, NE Bolivia, Clim Past Discuss, 11(1), 135–180, doi:10.5194/cpd-11-135-2015, 2015.

Markgraf, V. and Huber, U. M.: Late and postglacial vegetation and fire history in Southern Patagonia and Tierra del Fuego, Palaeogeogr. Palaeoclimatol. Palaeoecol., 297(2), 351–366, doi:10.1016/j.palaeo.2010.08.013, 2010.

Mayle, F. E., Burbridge, R. and Killeen, T. J.: Millennial-scale dynamics of southern Amazonian rain forests, Science, 290(5500), 2291–2294, doi:10.1126/science.290.5500.2291, 2000.

Mayle, F.E., Langstroth, R.P., Fisher, R.A., Meir, P.: Long-term forest-savannah dynamics in the Bolivian Amazon: implications for conservation. Philosophical Transactions of the Royal Society B: Biological Sciences 362, 291–307. doi:10.1098/rstb.2006.1987, 2007.

McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. and Reimer, P. J.: SHCal04 Southern Hemisphere calibration, 0–11.0 cal kyr BP, Radiocarbon, 46(3), 1087–1092, 2004.

McGee, D., Donohoe, A., Marshall, J. and Ferreira, D.: Changes in ITCZ location and cross-equatorial heat transport at the Last Glacial Maximum, Heinrich Stadial 1, and the mid-Holocene, Earth Planet. Sci. Lett., 390, 69–79, doi:10.1016/j.epsl.2013.12.043, 2014.

Melief, A. Late Quaternary paleoecology of the Parque Nacional Natural los Nevados (Cordillera Central) and Sumapaz (Cordillera Oriental) areas, Colombia. Ph.D. dissertation. University of Amsterdam, Amsterdam, The Netherlands, 162 pp, 1985.

Millard, A. R.: Conventions for reporting radiocarbon determinations, Radiocarbon, 56(2), 555–559, doi:10.2458/56.17455, 2014.

Mommersteeg, H.: Vegetation development and cyclic and abrupt climatic changes during the late Quaternary: palynological evidence from the Colombian Eastern Cordillera, Ph.D. thesis, Hugo de Vries Laboratory, University of Amsterdam, Amsterdam, Netherlands, 191 pp., 1998.

Mook, W. G. and Van der Plicht, J.: Reporting 14C activities and concentrations., Radiocarbon, 41(3), 227–239, 1999.

Muller, J.: Palynology of recent Orinoco delta and shelf sediments: Reports of the Orinoco shelf expedition, Micropaleontology, 5(1), 1–32, doi:10.2307/1484153, 1959.

Naranjo, J. A. and Stern, C. R.: Holocene tephrochronology of the southernmost part (42°30’-45°S) of the Andean Southern Volcanic Zone, Rev. Geológica Chile, 31(2), 224–240, doi:10.4067/S0716-02082004000200003, 2004.

De Oliveira, M. A. T., Porsani, J. L., de Lima, G. L., Jeske-Pieruschka, V. and Behling, H.: Upper Pleistocene to Holocene peatland evolution in southern Brazilian highlands as depicted by radar stratigraphy, sedimentology and palynology, Quat. Res., 77(3), 397–407, doi:10.1016/j.yqres.2011.12.006, 2012.

Ortega-Guerrero, B. and Newton, A. J.: Geochemical characterization of late Pleistocene and Holocene tephra layers from the basin of Mexico, Central Mexico, Quat. Res., 50(1), 90–106, doi:10.1006/qres.1998.1975, 1998.

Paduano, G. M., Bush, M. B., Baker, P. A., Fritz, S. C. and Seltzer, G. O.: A vegetation and fire history of Lake Titicaca since the Last Glacial Maximum, Palaeogeogr. Palaeoclimatol. Palaeoecol., 194(1-3), 259–279, doi:10.1016/S0031-0182(03)00281-5, 2003.

Parnell, A.C., Haslett, J,, Allen, J.R.M,, Buck, C.E,, Huntley, B.:. A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. Quat. Sci. Rev., 27, 1872-1885, doi: 10.1016/j.quascirev.2008.07.009, 2008

Povinec, P. P., Litherland, A. E. and Von Reden, K. F.: Developments in radiocarbon technologies: from the Libby counter to compound-specific AMS analyses, Radiocarbon, 51, 45–78, 2009.

Punyasena, S. W., Jaramillo, C., de la Parra, F. and Du, Y.: Probabilistic correlation of single stratigraphic samples: a generalized approach for biostratigraphic data, AAPG Bulletin, 96(2), 235–244, doi:10.1306/06201111026, 2012.

R Development Core Team, 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/, last accessed January 2015.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E. and Ruth, U.: A new Greenland ice core chronology for the last glacial termination, J. Geophys. Res., 111(D6), D06102, doi:10.1029/2005JD006079, 2006.

Recasens, C., Ariztegui, D., Gebhardt, C., Gogorza, C., Haberzettl, T., Hahn, A., Kliem, P., Lisé-Pronovost, A., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., St-Onge, G., Wille, M., Zolitschka, B. and Science Team: New insights into paleoenvironmental changes in Laguna Potrok Aike, southern Patagonia, since the late Pleistocene: The PASADO multiproxy record, The Holocene, 22(11), 1323–1335, doi:10.1177/0959683611429833, 2012.

Recasens, C., Ariztegui, D., Maidana, N. I. and Zolitschka, B.: Diatoms as indicators of hydrological and climatic changes in Laguna Potrok Aike (Patagonia) since the late Pleistocene, Palaeogeogr. Palaeoclimatol. Palaeoecol., 417, 309–319, doi:10.1016/j.palaeo.2014.09.021, 2015.

Reese, C. A.: Pollen dispersal and deposition in the high-central Andes, South America, Ph.D. Thesis, Department of Geography and Anthropology, Louisiana State University, Baton Rouge, USA, 132 pp., 2003.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., Van der Plicht, J. and Weyhenmeyer, C. E.: IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP, Radiocarbon, 46(3), 1029–1058, 2004a.

Reimer, P. J., Brown, T. A. and Reimer, R. W.: Discussion: Reporting and calibration of post-bomb 14C data, Radiocarbon, 46(3), 1299–1304, 2004b.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht, J.: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon, 55, 1869–1887, 2013.

Rodbell, D. T., Bagnato, S., Nebolini, J. C., Seltzer, G. O. and Abbott, M. B.: A late Glacial–Holocene tephrochronology for glacial lakes in southern Ecuador, Quat. Res., 57(3), 343–354, doi:10.1006/qres.2002.2324, 2002.

Rodriguez-Vargas, A., Koester, E., Mallmann, G., Conceição, R. V., Kawashita, K. and Weber, M. B. I.: Mantle diversity beneath the Colombian Andes, Northern Volcanic Zone: Constraints from Sr and Nd isotopes, Lithos, 82(3-4), 471–484, doi:10.1016/j.lithos.2004.09.027, 2005.

Roucoux, K. H., Lawson, I. T., Jones, T. D., Baker, T. R., Coronado, E. N. H., Gosling, W. D. and Lähteenoja, O.: Vegetation development in an Amazonian peatland, Palaeogeogr. Palaeoclimatol. Palaeoecol., 374, 242–255, doi:10.1016/j.palaeo.2013.01.023, 2013.

Rull, V., Stansell, N. D., Montoya, E., Bezada, M. and Abbott, M. B.: Palynological signal of the Younger Dryas in the tropical Venezuelan Andes, Quat. Sci. Rev., 29(23–24), 3045–3056, doi:10.1016/j.quascirev.2010.07.012, 2010.

Salomons, J.B.: Paleoecology of volcanic soils in the Colombian Central Cordillera. Dissertationes Botanicae, 95,1-212, 1986.

Seddon, A. W. R., Mackay, A. W., Baker, A. G., Birks, H. J. B., Breman, E., Buck, C. E., Ellis, E. C., Froyd, C. A., Gill, J. L., Gillson, L., Johnson, E. A., Jones, V. J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J. L., Nogués-Bravo, D., Punyasena, S. W., Roland, T. P., Tanentzap, A. J., Willis, K. J., Aberhan, M., van Asperen, E. N., Austin, W. E. N., Battarbee, R. W., Bhagwat, S., Belanger, C. L., Bennett, K. D., Birks, H. H., Bronk Ramsey, C., Brooks, S. J., de Bruyn, M., Butler, P. G., Chambers, F. M., Clarke, S. J., Davies, A. L., Dearing, J. A., Ezard, T. H. G., Feurdean, A., Flower, R. J., Gell, P., Hausmann, S., Hogan, E. J., Hopkins, M. J., Jeffers, E. S., Korhola, A. A., Marchant, R., Kiefer, T., Lamentowicz, M., Larocque-Tobler, I., López-Merino, L., Liow, L. H., McGowan, S., Miller, J. H., Montoya, E., Morton, O., Nogué, S., Onoufriou, C., Boush, L. P., Rodriguez-Sanchez, F., Rose, N. L., Sayer, C. D., Shaw, H. E., Payne, R., Simpson, G., Sohar, K., Whitehouse, N. J., Williams, J. W. and Witkowski, A.: Looking forward through the past: identification of 50 priority research questions in palaeoecology, J. Ecol., 102(1), 256–267, doi:10.1111/1365-2745.12195, 2014.

Steinitz-Kannan, M., Riedinger, M. A., Last, W., Brenner, M. and Miller, M. C.: Un registro de 6000 años de manifestaciones intensas del fenómeno de El Niño en sedimentos de lagunas de las Islas Galápagos, Bull Inst Fr Etudes Andin., 27(3), 581–592, 1998.

Stern, C. R.: Active Andean volcanism: its geologic and tectonic setting, Rev. Geológica Chile, 31(2), 161–206, doi:10.4067/S0716-02082004000200001, 2004.

Stuiver, M. and Polach, H. A.: Discussion; reporting of C-14 data., Radiocarbon, 19(3), 355–363, 1977.

Sundqvist, H. S., Kaufman, D. S., McKay, N. P., Balascio, N. L., Briner, J. P., Cwynar, L. C., Sejrup, H. P., Seppä, H., Subetto, D. A., Andrews, J. T., Axford, Y., Bakke, J., Birks, H. J. B., Brooks, S. J., de Vernal, A., Jennings, A. E., Ljungqvist, F. C., Rühland, K. M., Saenger, C., Smol, J. P. and Viau, A. E.: Arctic Holocene proxy climate database ; new approaches to assessing geochronological accuracy and encoding climate variables, Clim. Past., 10, 1605-1631, doi:10.5194/cp-10-1605-2014, 2014.

Telford, R. J., Heegaard, E. and Birks, H. J. B.: All age–depth models are wrong: but how badly?, Quat. Sci. Rev., 23(1–2), 1–5, doi:10.1016/j.quascirev.2003.11.003, 2004.

Torres, V., Vandenberghe, J. and Hooghiemstra, H.: An environmental reconstruction of the sediment infill of the Bogotá basin (Colombia) during the last 3 million years from abiotic and biotic proxies, Palaeogeogr. Palaeoclimatol. Palaeoecol., 226(1-2), 127–148, doi:10.1016/j.palaeo.2005.05.005, 2005.

Traverse, A. Paleopalynology. Unwin/Hyman Ltd., Boston-London, 600 pp., 1988.

Tsudaka, M.: The pollen sequence, in: Cowgill, U., Goulden, C.E., Hutchinson, G.E., Patrick, R., Racek, A.A., Tsudaka, M. (Eds.), The history of Laguna Petenxil, a small lake in northern Guatemala, Memoir 17, Connecticut Academy of Arts and Sciences, New Haven, USA, 63–66, 1967.

Urrego, D. H., Bernal, J. P., Chiessi, C. M., Cruz, F. W., Sanchez Goñi, M. F., Power, M., Hooghiemstra and LaAcer participantes: Millennial-scale climate variability in the American tropics and subtropics, PAGES Mag., 22(2), 94–95, 2014.

Van der Hammen, T.: Data on the history of climate, vegetation and glaciation of the Sierra Nevada de Santa Marta, in La Sierra Nevada de Santa Marta (Colombia), Transecto Buritaca-La Cumbre. Estudios de ecosistemas tropandinos, edited by Van der Hammen, Thomas and P. M. Ruiz, Cramer (Borntraeger), Berlin/Stuttgart, Germany., 561–580, 1984.

Van der Hammen, T.: La ultima glaciación en Colombia (Glaciacion Cocuy; Fuquense). Análisis Geográficos, 24, 69-89, 1995.

Van der Hammen, T. and González, E.: Upper Pleistocene and Holocene climate and vegetation of the "Sabana de Bogotá" (Colombia, South America), Leidse Geol. Meded., 25, 261–315, 1960.

Van der Hammen, T. and González, E.: A late-glacial and Holocene pollen diagram from Cienaga del Visitador Dep. Boyacá, Colombia, Leidse Geol. Meded., 32, 193–201, 1965.

Van der Hammen, T. and Hooghiemstra, H.: Cronostratografia y correlacion del Plioceno y Cuaternario en Colombia, Análisis Geográficos, 24, 51-67, 1995a

Van der Hammen, T. and Hooghiemstra, H.: The El Abra stadial, a Younger Dryas equivalent in Colombia, Quat. Sci. Rev., 14, 841–851, 1995b.

Van der Hammen, T. and Hooghiemstra, H.: Interglacial–glacial Fúquene-3 pollen record from Colombia: an Eemian to Holocene climate record, Glob. Planet. Change, 36(3), 181–199, doi:10.1016/S0921-8181(02)00184-4, 2003.

Van Geel, B. and Van der Hammen, T.: Upper Quaternary vegetational and climatic secuence of the Fúquene area (Eastern Cordillera, Colombia), Palaeogeogr. Palaeoclimatol. Palaeoecol., 14, 9–92, 1973.

Van Meerbeeck, C. J., Renssen, H. and Roche, D. M.: How did Marine Isotope Stage 3 and Last Glacial Maximum climates differ?–perspectives from equilibrium simulations, Clim. Past, 5(1), 33–51, 2009.

Vaughan, H.H., Deevey, E. S. J. and Garrett-Jones, S. E.: Pollen stratigraphy of two cores from Petén lake district, in: Pohl, M.D. (Eds.), Prehistoric lowland Maya environment and subsistence economy, Harvard University, Cambridge, USA, 73–89, 1985.

Velásquez-R, C.A., Parra S., L.N., Sánchez S., D., Rangel-Ch., J.O., Ariza N., C.L. and Jaramillo J., A.: Tardiglacial y Holoceno del norte de la Cordillera Occidental del Colombia, Universidad Nacional de Medellín, Medellín, Colombia, 236 pp., 1999.

Vélez, M. I., Hooghiemstra, H., Metcalfe, S., Martínez, I. and Mommersteeg, H.: Pollen- and diatom based environmental history since the Last Glacial Maximum from the Andean core Fúquene-7, Colombia, J. Quat. Sci., 18(1), 17–30, doi:10.1002/jqs.730, 2003.

Vogel, J. C. and Lerman, J. C.: Groningen radiocarbon dates VIII., Radiocarbon, 11(2), 351–390, doi:10.2458/azu_js_rc.11.204, 1969.

Wigley, T. M. L. and Muller, A. B.: Fractionation correction in radiocarbon dating, Radiocarbon, 23(2), 173–190, 1981.

Wijninga, V. M.: A Pliocene Podocarpus forest mire from the area of the high plain of Bogotá (Cordillera Oriental, Colombia), Rev. Palaeobot. Palynol., 92, 157–205, 1996.

Maximum distance to the nearest data (yr)	Stars	Colorbar Fig. 2
2000	1	Green
1000	2	Dark blue
500	3	Light blue
Straight segment	+1	Red

Table 1. Classification of sample age uncertainty from the star classification system (Adapted from Giesecke et al., 2014)

Figure 1. Pollen records currently present in the Neotropical Geochronological database. All records contain at least one geochronological date.

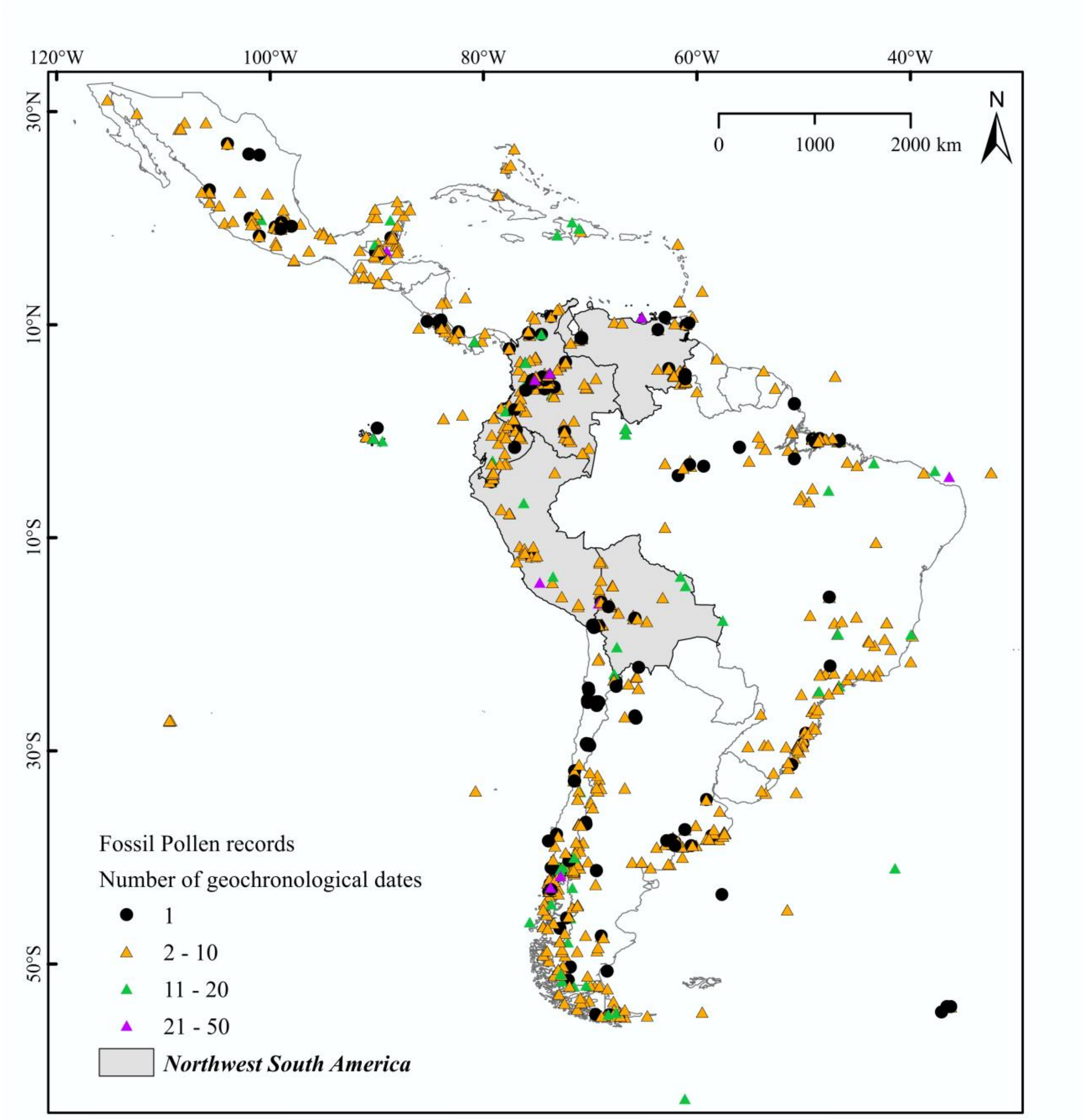

Figure 2. Recalibrated age depth relationship from Laguna Chaplin A (Mayle et al., 2007). The green, dark blue, light blue bars along the vertical axis reflect the proximity of a sample to the

nearest control points, from ‘far’, ‘good’, ‘best’ respectively. The red bar marks samples within a segment of the core supported by at least four control points within which the sediment accumulation changes less than 20 %. The addition of an additional upper age estimate would better constrain the extrapolation toward the top, which otherwise yield ages that are too young as shown in this example. The blue polygons at the control points represent the calibrated age range as a distribution, where the height of the polygon provides an indication of the probability of the age obtained from the control point. The dark bar alongside is shown as an example where the interpretation of the chronology can be supported by the lithological information alongside.

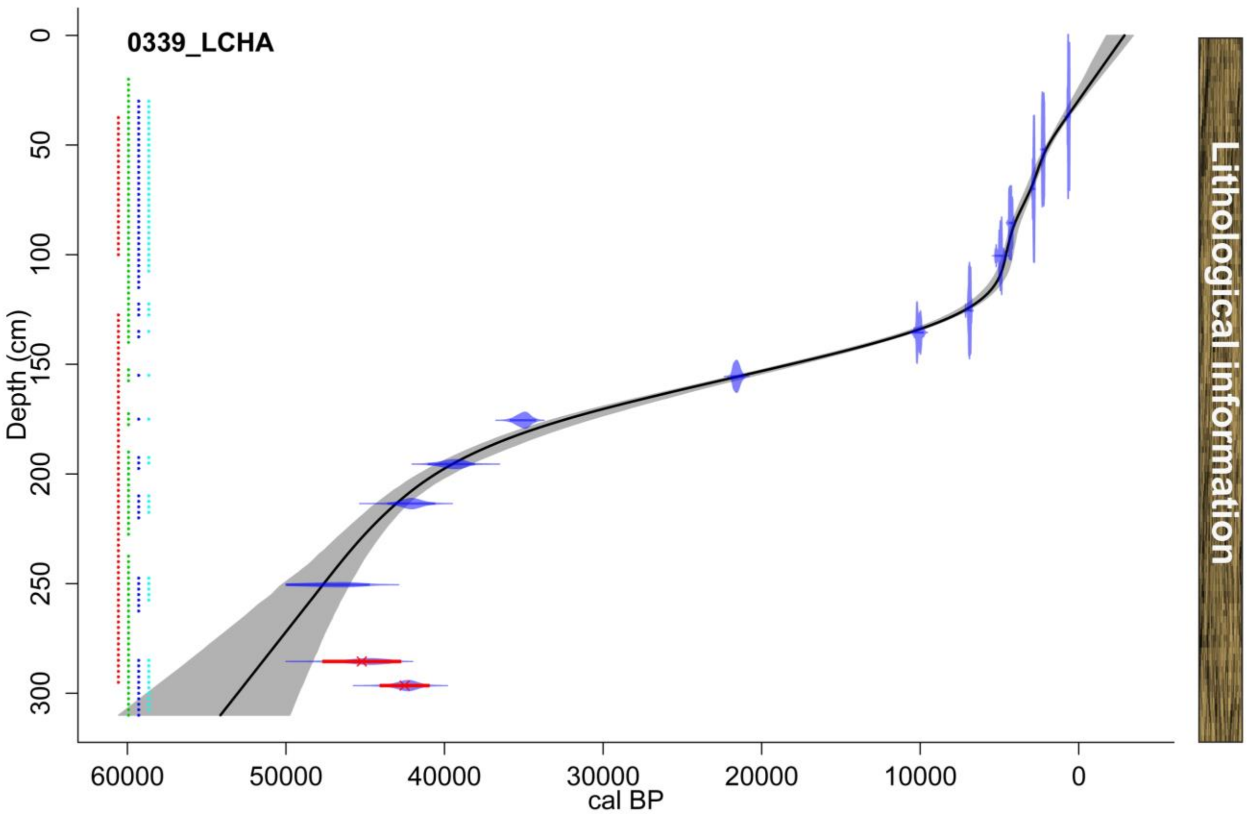

Figure 3. Temporal uncertainty assessment on recalibrated control points and age models in northwest South America. A) Number of stars assigned to samples of recalibrated chronologies (normalized to 100%). B) Median value of stars and resolution of the recalibrated chronologies. The small window displays the region of the Galapagos Islands and the marine core ODP677.

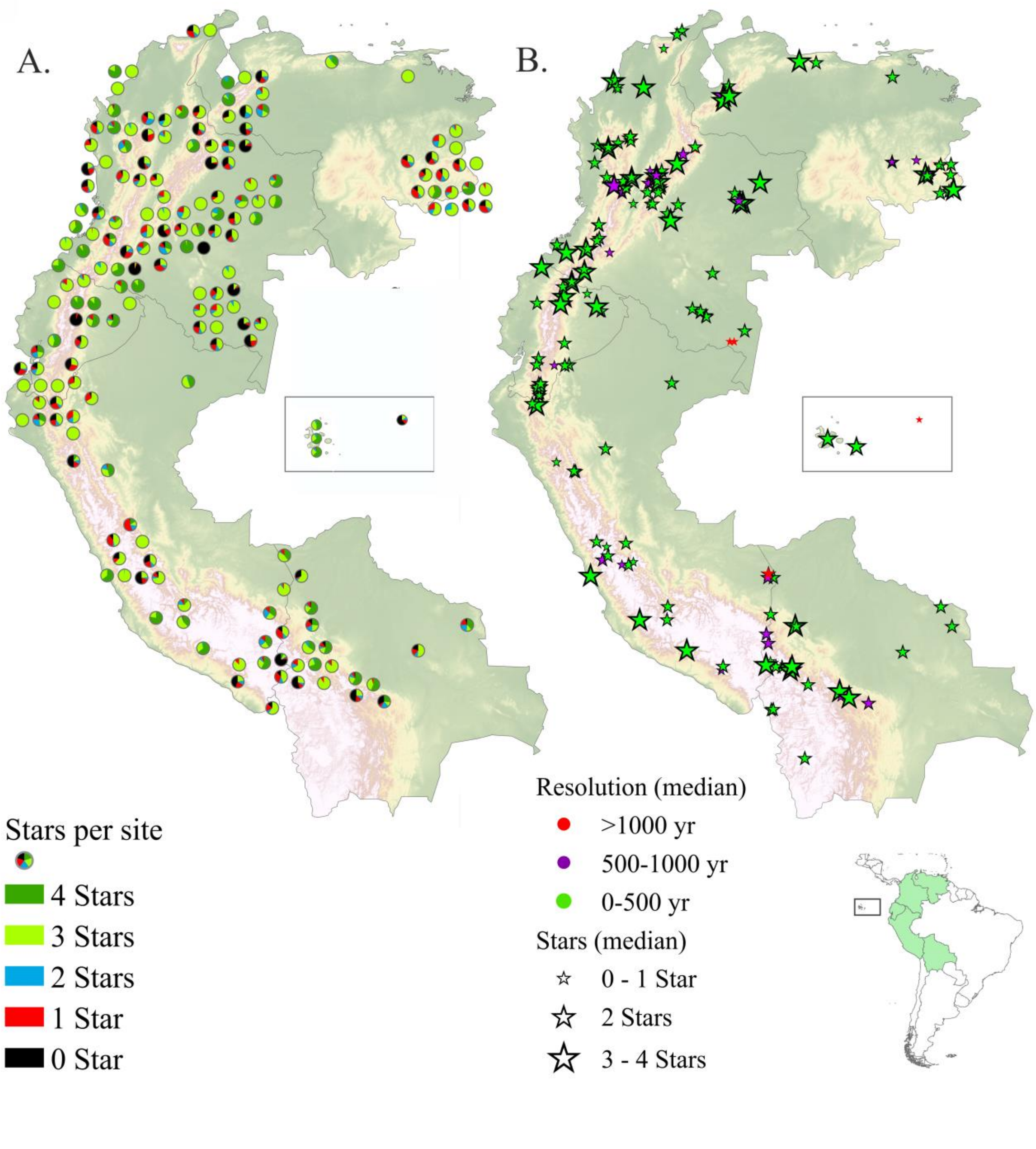

Figure 4. Histograms depicting the star classification outcome on sample level (A, C) and sites (B, D) for the last 60 kcal BP. Histograms A) and B) depict the MIS 3 (at 1000 yr time bins) and histograms C and D the last 25 kcal (at 500 yr bins). The height of the bar indicates the number of samples or sites with a certain number of stars. The different colours illustrate the number of stars assigned for that time bin. Samples and sites beyond 60 kcal BP were not presented due to the very low number of sites available (Fig.5).

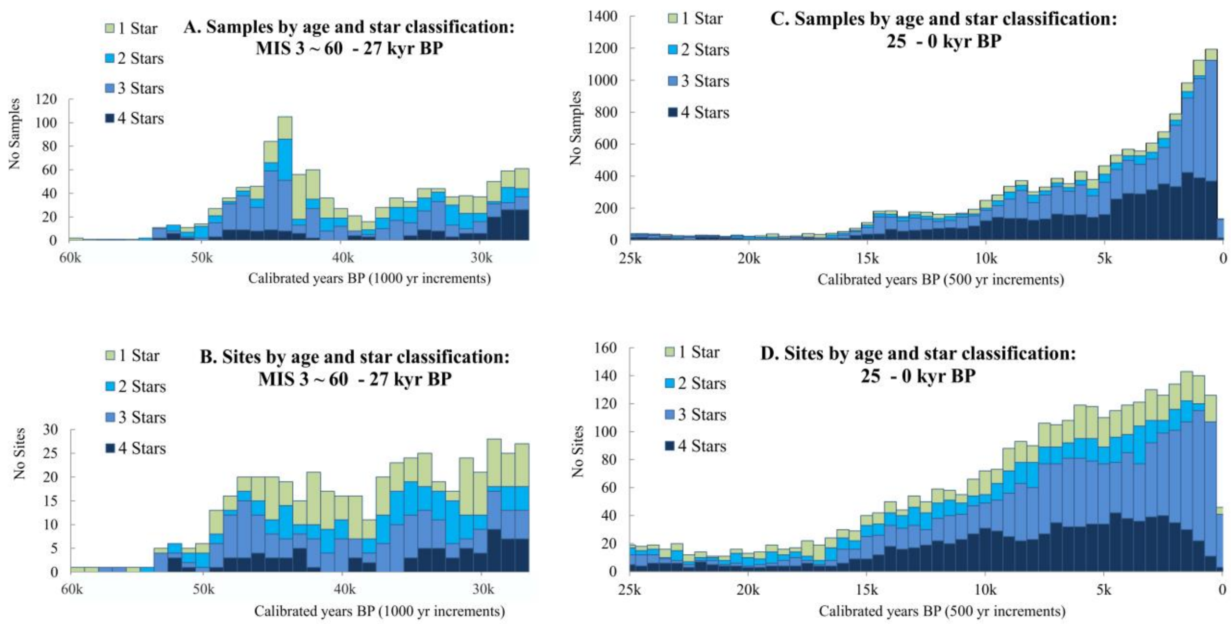

Figure 5. Changing mean sample resolution (left) and mean number of stars (right) of the pollen database of northwest South America during the period 100 kcal to -50 cal yr BP.