February 2nd 2016

Dear Editor,

Please find below our detailed replies (in blue) and corresponding adjustments of our manuscript consequently to the comments and suggestions formulated by the two reviewers and your final advice from the 28th of January. Enclosed is the revised version of the manuscript with all modifications highlighted in color.

The most important adjustments have been:

- We have put special attention to restructuring the introduction-methods-results,
- Improvements to (sub-) titles;
- Filtering text without significant contribution to the aims of the paper;
- Availability of data: The paper is accompanied by a figshare link where not only all age models are available with their corresponding descriptions, but furthermore the R-scripts to run the star classification system is free of use. We included a README file with easy-to-follow instructions. We aim to have this manual both in English and Spanish, and we will be continuously updating the document with feedback from users.
- We moved the information from the Supplementary Information to the main text. This information includes a long table with all the pollen records for which we studied the age models (now Table 1) and their references (now incorporated within the reference list). We fully agree that this improvement was necessary and that this information is better placed within the body of the manuscript itself.

We hope we successfully complied with the comments and suggestions and we feel that the manuscript has improved greatly.

Best regards,
Suzette Flantua, Maarten Blaauw & Henry Hooghiemstra

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Response to T. Giesecke: Interactive comment on "Quality assessment of chronologies in Latin American pollen records: a contribution to centennial to millennial scale studies of environmental change" by S. G. A. Flantua, H. Hooghiemstra, and M. Blaauw. doi:10.5194/cpd-11-1219-2015

We much appreciate the review report on our paper and we found it very helpful indeed to prepare an improved draft. We have included nearly all suggestions in the text and here we address each comment with explanation.

1) The authors need to make the results of their work available with this publication.

- This is a very good suggestion, thank you. We will make all chronologies, R code and results of star classification available as a dataset in a publically accessible data depository.

2) Flantua et al. adopt the age uncertainty reporting from the EPD (which needs to be cited as Giesecke et al. 2014) but focus in the text only on the classification system based on the density of dates in time. Giesecke et al. 2014 stress that this classification has to be used in conjunction with the propagation of age uncertainty from the dates through the age model. The intention of this system was also to provide information for individual samples in a database rather than for full records, as dating control often varies through the record.

- We updated the reference Giesecke et al. 2014 in the paper, thank you for the correction.

- Concerning the lacking information on the classification system for individual samples, we could not go into that detail within this paper. As we are aware of this specific recommendation mentioned by Giesecke et al., 2014, we think that by making all results available, researchers will have the necessary data to use the classification at the level of the record and individual samples throughout the age model. To reinforce the importance of the assessment at different levels, we will include the comment from the reviewer in the final section: "Dating 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".

3) Flantua et al. discuss sources of age information including seismic activities that were not discussed by Giesecke et al. 2014, however, I missed a discussion on the uncertainties of these types of age information. Particularly in the case of biostratigraphic dates, the situation in South America is certainly more complex than in Europe. However, the information that samples date to the Lateglacial versus the Holocene is still important information that could be used in Bayesian methods without causing circularities.

Thank you for this observation. Indeed we discuss uncertainties of radiocarbon dates, but we did not address chronological uncertainties of tephra, seismic activities and OSL. Therefore in Section. 3.1 we will briefly discuss potential sources of these uncertainties.
For tephrochronology and OLS we will use: 1) Lowe, D.J., 2008. Uncertainty in tephrochronology. SUPRAnet consortium workshop 'Studying uncertainty in palaeoclimate reconstruction', Sheffield, U.K., 23-27 June 2008. Presentation available at http://caitlinbuck.staff.shef.ac.uk/; 2) Lowe D.J. (2011) Tephrochronology and its application: A review. Quaternary Geochronology, 6, 107–153.
In the case of biostratigraphy we will address uncertainty using Gladenkov Y.B. (2010) Zonal biostratigraphy in the solution of the fundamental and applied problems of geology. Stratigraphy and Geological Correlation, 18, 660–673.
Concerning chronological uncertainties in seismic activities, we decided to remove this section.

4) I am also curious how bottom ages were derived and why you think that 50 years is an adequate age uncertainty for all core tops while we used uncertainties of up to 250 years in Europe.

- Concerning bottom ages we mention P1225, l.24: "Similarly we did not use the basal ages of the authors when based on extrapolations, but allowed the recalibrated age model produce new down-core ages". With this we mean that we used the recalibrated age model to produce the bottom ages.

- Concerning the core tops, we have adjusted the text (P1225, l.20) to explain that only when the authors from the original age model claim to have certainty over the core top (being the sampling year or not), did we use an uncertainty of ±50. We did not use any of the estimated core tops, but as with the bottom ages, let the recalibrated age model produce the ages of the core tops. We decided to use the uncertainty range of ±50 considering that this standard deviation results in ca. 300yr of total uncertainty. We consider this value an appropriate estimate of uncertainty of core top ages. As we will be providing the R-code, anyone interested may adjust this value accordingly.

5) I find the discussion of uncertainties of age estimates important including the shape of particular probability distributions, as Bayesian methods can use them in a statistical way.

- Thank you.

6) The title, abstract and introduction should reflect the two different results presented, namely a database containing all dating information for all Latin America and new age models for north-west South America.

- Thank you for this very valuable suggestion. We adjusted the title and modified the abstract and introduction accordingly.

7) I also do not understand the reason for focusing on the different time periods in this manuscript. I gather that this manuscript is part of a special issue and can imagine that another paper refers to these periods. Otherwise, I cannot see the value of singling out particular periods in the presented manuscript and would consider removing it.

- We understand that being part of the Special Issue of "Millennial-scale variability in the American tropics and subtropics" and the INQUA workgroup of LaACER (Latin-American Abrupt Climate Changes and Environmental Responses) has been insufficiently addressed. We aimed to fulfill the specific goals of the Special Issue and workgroup, but understand that the selection of time periods caused confusion. Therefore we will make important adjustments to main thread of the paper to improve the general context of this study and clarify the aims and purposes of the paper. We do believe that it is valuable to present a full analysis of chronologies from MIS5 to the present independently of the purpose of the Special Issue. The time windows we discuss are continuous and specifying these periods facilitates the integration of results into other initiatives. Therefore removing a figure such as Figure 3, which provides an important overview of the last 60 kyr BP, would exclude the discussion on the late Holocene chronologies.

9) The text is in some sections unnecessary long as it includes anecdotal accounts on particularities of different sites that could be reduced or omitted altogether. Also some in-between explanations are not always needed and make the text unnecessarily long e.g. the explanation of conventional radiocarbon dates P. 1229, L. 10ff.

- Thank you for this observation. We reduced text throughout section 3.1 Control Points.

10) The title is unfortunate as it suggests the assessment of the quality of work of other palaeoecologists whose data are used.

- We understand the confusion of the suggestive title on data assessment. Therefore the title has been adjusted.

11) Also in the text the authors should consider that the purpose of the individual contributions that were reviewed was not to contribute to large-scale analysis but to address a local problem.

- Thank you for this suggestion. In the introduction we added the phrase: An additional difficulty is that the development of large-scale analyses is relatively recent, demanding occasionally a different approach to and data handling of individual pollen records. The latter were most often developed to explore questions on a local or regional terrain, unacquainted with requirements for multi-site integration.

12) P. 1220, L. 4: This is a strong statement and maybe not what you mean to express.

- We understand that the statement “Heterogeneous paleoecological databases are not suitable to be integrated without an uncertainty assessment of existing chronologies” might be strong, but we consider that uncertainty assessment of chronologies should be a first step in all multi-site and multi-proxy studies before making statements on observed “synchronous” events. To smooth off the rough edges of the statement, we changed it to: “However, all efforts to integrate paleoecological databases would highly benefit from an uncertainty assessment of existing chronologies”.

13) The LAPD is not a heterogeneous database (see also P. 1221, L. 10) as it contains only pollen data. The age control between sites is heterogenic, hampering detailed comparisons and meta-analysis.

- Thank you for this observation. We removed “heterogeneous” in P.1221, L 10 as it is actually redundant.

13) P. 1221, L. 24 and throughout: You probably mean Giesecke et al. 2014 rather than 2012.

- Yes, thank you for this correction. We had an older version of this paper where 2012 was mentioned, but now we corrected this throughout the paper.

14) P. 1222, L. 20: Our intention was to describe the age uncertainty for individual samples rather than sites. In that system the classification needs to be combined with the uncertainty from the age model.

- We regard the purpose of this paper to provide an overview at the level of the sites. By providing all produced results and mentioning the importance of combining the assessment at the age model and sample level (now addressed in the Conclusions and Recommendations), each researcher has the possibility to review the findings and use them accordingly. The

Supplementary information will contain the star results for the entire sites and individual depths per site.

15) P. 1225, L. 9-10: Confusing statement please consider revising.

- We adjusted the statement to: 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, 1995) are commonly used biostratigraphic dates within Colombia. These periods are considered to be equivalent to the European Allerød Interstadial and the Younger Dryas sequence, respectively (van der Hammen and Hooghiemstra, 1995).

16) P. 1225, L. 21: What do you mean by 1 SD in brackets after 50 year uncertainty?

- Without further explanation, we understand that this comment causes confusion. We removed “1SD”.

17) P. 1228, L. 14: The explanation of the abbreviation kyr BP in between MIS 5 and MIS3 is confusing.

- We adjusted this sentence as followed: Therefore, we focused on the following time windows: MIS 5 (c. 130–70 thousand years before present, here abbreviated to kyr BP), MIS 3 (c. 60–27 kyr BP), Heinrich event 1 (H1; c. 18–15 kyr BP), and the YD/Holocene transition (c. 12.86–11.65 kyr BP).

18) P. 1228, L. 14ff: I would assume that few records fall into this time period. Why was there no focus on a period in the Holocene, e.g. the moisture increase during the late Holocene? See also general comment on time periods.

- We understand that the reviewer would have preferred additional assessments on other periods of time. Within the projects in which we collaborated, the main focus has been on rapid climate events over a longer time period, such as the MISs here shown. Now that all results are made available, we hope that other researchers will elaborate more on other time periods such as changes during the Holocene.

19) P. 1229, L. 26: New sentence starts with citation in brackets.

- Corrected, thank you.

20) P. 1235, L. 19: It should be made clear that this is what was submitted by the authors or reported in publications. The heading is not reflecting the content of this section.

- We adjusted the heading to: Current age models and calibration curves

21) P. 1237, L. 4-5: The star assignment is fairly simple and I suppose M. Blaauw could either fix the R-code to make it more robust or the classes could be assigned manually.

- We agree that the star assignment system can be further developed to also solve the problem here mentioned that: "The star system classification did not assign stars to 4 chronologies, when the calibrated ages overlapped over a very short time range creating conflicts within the star calculation function". We think that for now this simple approach is sufficiently suitable for the wide range of age models assessed here, leaving open the possibility to improve the star classification system in collaboration with other researchers on South America.

22) P. 1237, L. 23: May this be due to the fact that the top is a date for a large number of sites?

- Probably not, because from many sites we did not use their top age when based on an estimate solely. Only sites with a measured top age were used.

23) P. 1240, L. 20ff: In discussion on why people are not using Bayesian methods I miss the motivation of why the presented study did not use these tools.

- Very good observation, thank you. As we describe for the example of applying Bayesian methods (P. 1236, L.13), these authors used "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 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. In a paper currently in preparation, Blaauw et al will address the fact that even if the 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.

Therefore we mention at P. 1241, L. 8: Researchers should 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.

24) P.1242, L. 15-16: The stars are only a classification of the temporal density of radiocarbon dates and need to be considered in conjunction with the age uncertainties provided by the age depth model.

- We added this important comment to the Conclusion and Recommendations section, thank you.

25) P. 1242, L. 25: I appreciate your frustration with the reporting of age determinations, but would disagree in two points: 1) the original research question leading to a site based investigation may NOT require detailed chronological information. 2) Ideally the information should be submitted by the authors to database and may not need to be presented in full in the publication.

- We understand your comment more as an additional recommendation than as a disagreement with our statement that "it is important that authors report at the necessary detail the chronology of their sediment core". Research questions may not have the purpose to develop detailed chronological information, but all studies considering a temporal feature should provide at least the minimum chronological backup to support their temporal assessment and statements. We encourage researchers who currently do not report the basic chronological information (e.g. depths of ^{14}C dates, calibration method used, etc.), to work within a minimum set of information. We agree with the second suggestion of the reviewer that submitting the information to a database would be an important achievement.

Response to MP Ledru: Interactive comment on "Quality assessment of chronologies in Latin American pollen records: a contribution to centennial to millennial scale studies of environmental change" by S. G. A. Flantua, H. Hooghiemstra, and M. Blaauw. doi:10.5194/cpd-11-1219-2015

We much appreciate the review report on our paper and we found it very helpful indeed to prepare an improved draft. We have included nearly all comments in the text and here we address each comment with explanation.

1) I understand that this paper is part of a special issue on the last termination. However I can see it is actually (at least) two different papers in one: i) a quality assessment of the chronology of the pollen database for NW-SA, and ii) the use of the database to characterize the last termination. The second part could come as a regional application of the quality assessment of the data. In this case, it needs to be better separated from the first part. In addition, the whole section 3 is dedicated to presenting the LAPDChronDB, which is off topic, as it is neither the NW-SA nor the last termination. This is an excellent paper which certainly deserves publication in Climate of the Past. However the main thread of the paper is not clear and the paper thus requires major reorganization before being published.

- Thank you for this valuable comment. To improve the structure of the paper and to explain better the connection between both sections, we made adjustments in the Title, the Abstract, Introduction and structure of the Methods. In the improved draft of the manuscript we aimed at providing a much improved structure set out to the reader within the context of our working group.

2) The title is not representative of the content of the paper, although this is perhaps because I am confused about the main subject of the paper.

- Thank you for this suggestion. We adjusted the title.

3) The authors mention they have been re-calibrating all the data, but it is not clear why.

- This is an important observation and we are grateful for the comment. Updated calibration curves (currently IntCal13/SHCal13; Reimer et al. 2013; Hogg et al. 2013) reflect our latest understanding of how 14C ages fluctuate over calendar time, and recalibrating 14C dates with the latest calibration curve will result in better age estimates. Many of the sites within the database were analysed using calibration curves that have now become obsolete. In section 2.2 Chronology evaluation for Northwest South America we added an additional explanation: New chronologies were generated with updated calibration curves to be able to implement the star classification system and to provide alternative chronologies to the researchers from the original chronologies to evaluate possible differences between calibration curves.

4) We would need an example of the possible benefits of re-calibration. How are the authors going to use their re-calibrated data? What do they intend to suggest to those who want to download the metadata from Neotoma and use a proper age model? Could they use the new one, if it is accessible?

We will make all results available through the supplementary information of CP and Fig.Share, the LAPD website (will be launched shortly) and as an additional feature in Neotoma. Thank you for the suggestion.

5) Other methods (including probability density functions) have been tested to avoid discussing the quality of an age model when one wants to use pollen counts that do not support a good chronological control (see for instance Hély et al. 2014). These methods should be added to the discussion. Hély, C., A.M. Lézine, and APD contributors. 2014. Holocene changes in African vegetation: tradeoff between climate and water availability. Climate of the Past 10: 681-686.

Thank you for the suggested reference. In the section 4.2 Temporal uncertainty assessment of chronologies we added a comment considering the use of probability density function with Hély et al., 2014 as an example.

6) Seismic activities page 1233, line 33-39 The gaps in the records from the Choco are probably due to seismic activity but never show synchroneity (see also Lim et al. 2014).

This observation is corrected. From Urrego et al. 2006 we assumed more synchronicity than actually occurred. We have removed this section totally as we felt that it was not adding more to the discussion of the paper.

7) The discussion about the use of the NH or of the SH correction in the section 3.3 Calibration curves and software is interesting. Why don't you give an example of a calculation using the two corrections and show the time difference?

The existence of a ^{14}C age difference of up to a few decades between the northern and southern hemisphere is well known and has been discussed extensively in the literature, e.g. McCormac et al. 1998 (Geophysical Research Letters 25(9), 1321-1324; Turkney & Palmer, 2007 (Quaternary research 67(1), 174-180; Hogg et al. 2013 (Radiocarbon 55, 1889–1903). The difference between the NH and SH calibration curve is ca. 40yr but differs in time. Therefore we do not think that showing examples of ^{14}C dates calibrated with IntCal13 and SHCal13 is particularly relevant for our current paper.

8) Concerning the description of sedimentation conditions (p. 1241 line 8-9), this is an important piece of information and should be discussed earlier as, apart from BACON software, age models rarely take this point into consideration.

Thank you for this comment. We added at P.1236 L.15 the following phrase: 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.

9) The Bayesian approach (section 4.2) should appear in the age model, in the methods section 2.3.

We moved the section on Bayesian approach from the Discussion section to the Results section. Thank you for this suggestion.

10) Figure 3: Would MIS 3 stand as an example of the use of re-calibration?

Yes. The re-calibration was aimed to a) provide alternative age models for those records without age models or with only linear interpolation; b) implement the star classification system on the updated age models; c) use the new, longer calibration curve, which now covers the MIS3, for southern hemisphere records. We included an additional comment to the figure caption to emphasize this.

11) Does figure 3 show the results of NW-SA or LAPD? Why only MIS 3? Why not all the data for NW-SA?

To create Fig. 3 data from NW-SA were used. We decided not to use the chronologies beyond MIS3 because of the very low number of sites available (Fig. 3b and Fig.4).

12) The following references should be added: Blaauw and Christen, 2011 Maezumi et al., 2015

- We checked these references both in the text (both on P. 1236) as also in the reference list, and they were correctly mentioned in the current paper. We are not sure what else the reviewer could be meaning.

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]

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[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, Cleef, A., 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. Rodríguez, V. Rull, M.L. Salgado-Labouriau, J.B. Salomons, E.J. Schreve-Brinkman, L.E. Urrego, Van der Hammen, T., 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) and H. Hooghiemstra (H.Hooghiemstra@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 234 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

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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 age models and developed R scripts are publically available through *figshare*, including a manual to use the scripts.

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

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- **Moved up [1]:** New chronologies are generated for 233 pollen records based on updated calibration curves.
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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; 2015; 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 figshare at: https://figshare.com/s/0e9afb8fe758a0e6e8c8.

2 Methods

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However, temporal uncertainty remains a challenge in heterogeneous databases of fossil-pollen records (Blois et al., 2011). The demands for precise and accurate chronologies have increased and so have the questions needing high-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 extremely precise ...

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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., 2015). 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 234 pollen records (Table 1). 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.

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To assess the temporal uncertainty of chronologies within a specific region of interest, namely NW-SA, the following steps were undertaken: From the LAPD-ChronDB, all sites present in Venezuela, Colombia, Ecuador, Peru and Bolivia were selected (Fig.1 in grey). When more than one chronological date was available, new chronologies were generated with the updated calibration curves for the northern and the southern hemisphere and maintained as closely as possible to the authors' interpretation of the age model (Section 2.3). The quality evaluation of age models consists of implementing the method proposed by Giesecke et al. (2012) and will be explained in the Section 2.4, followed by temporal resolution estimates at an site specific and synoptic level within different time windows (Section 2.5). ¶

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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 layers from volcanic material, radioactive lead isotopes (^{210}Pb) and fission track dates.

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

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Although high resolution well dated pollen records are becoming available, f

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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 reevaluation. 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

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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.

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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.

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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 2). 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

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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., 2015). 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., 2015). 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

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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

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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, 2008; 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; Rodríguez-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 et al., 1999) make use of these events in their chronologies. Even sites along the Eastern Cordillera capture these volcanic ashes, like

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Funza (Andriessen et al., 1994; Torres et al., 2005) and El Abra (Kuhry et al., 1993), while the ridge itself lacks volcanic activities (Rodríguez-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; Rodríguez-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

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(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).

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Other dating techniques

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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.

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In some cases, significant seismic events can be observed synchronously in various pollen records. For example, over a large area in the Chocó Biogeographic region, synchronous gaps in records were probably caused by a floodplain subsidence of a delta in the Colombian Pacific region (Berrío et al., 2000; González and Correa, 2001; Urrego Giraldo and del Valle A., 2002; Urrego et al., 2006). These events of high seismic activities can provide additional support for pinpointing chronologies when recorded as analogues events in different records.
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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

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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

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'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)

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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 (Table 1), 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-Angel et al., 2011). Research into millennial-scale climate variability is difficult

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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., 2015), 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., 2015), 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).

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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

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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., 2011a). 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

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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–

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environmental interactions in which pollen records in Central and South America are a vital source of information (Flantua et al., 2016).

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.

Supplementary information from this paper (all outcomes, R-scripts and manual in English and Spanish is available at figshare: https://figshare.com/s/0e9afb8fe758a0e6e8c8.

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Table 1. List of sites for which age models were recalibrated

Table 2. Classification of sample age uncertainty from the star classification system (Adapted from Giesecke et al., 2014)

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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

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

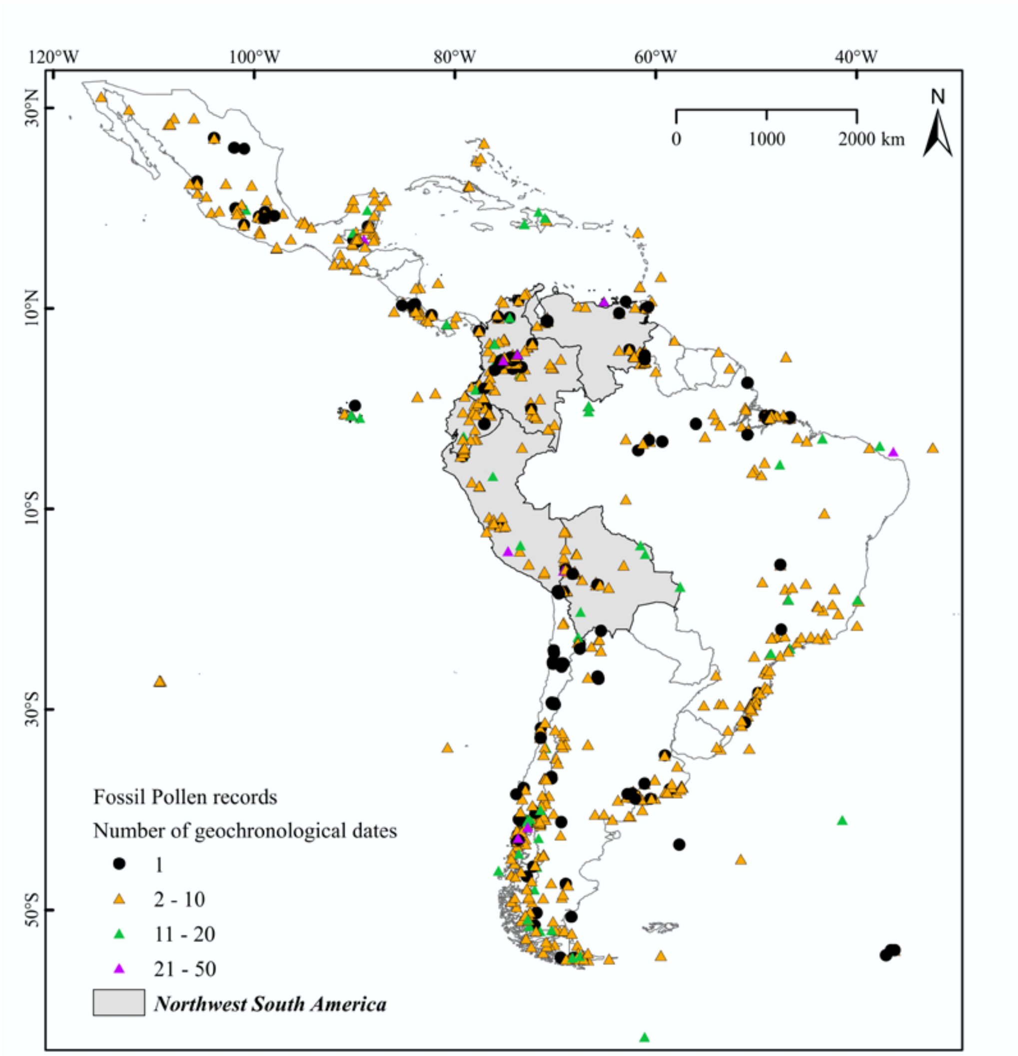

Figure 2. Recalibrated age depth relationship from Laguna Chaplin A (Mayle et al., 2007). The green, dark blue, light blue bars along the vertical axis reflect the proximity of a sample to the

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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.

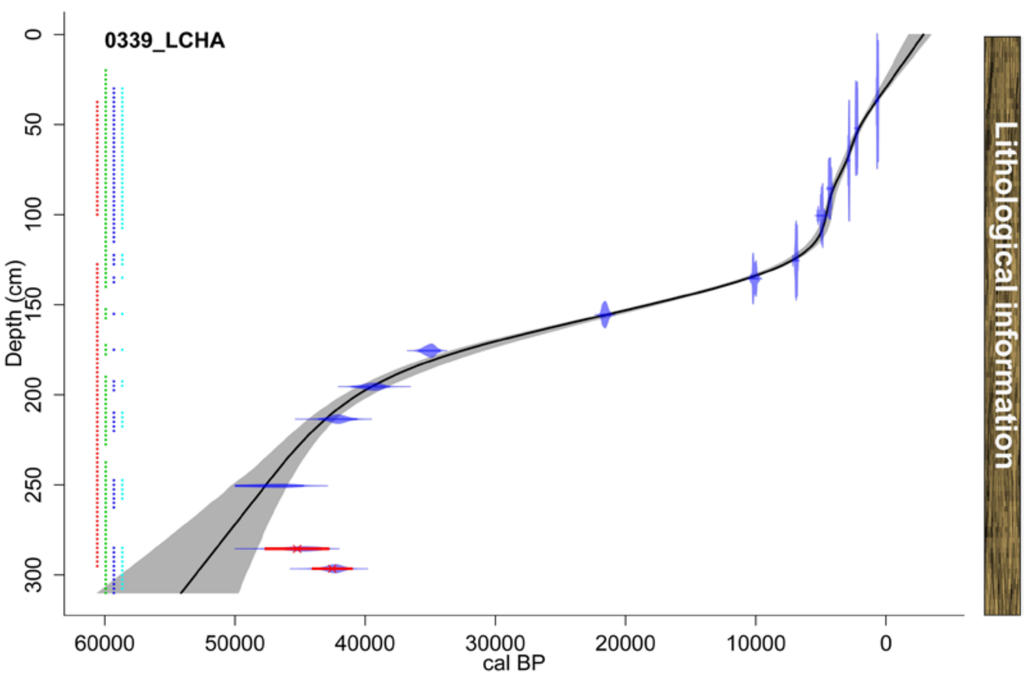

Figure 3. Temporal uncertainty assessment on recalibrated control points and age models in northwest South America. A) Number of stars assigned to samples of recalibrated chronologies (normalized to 100%). B) Median value of stars and resolution of the recalibrated chronologies.

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The small window displays the region of the Galapagos Islands and the marine core ODP677.

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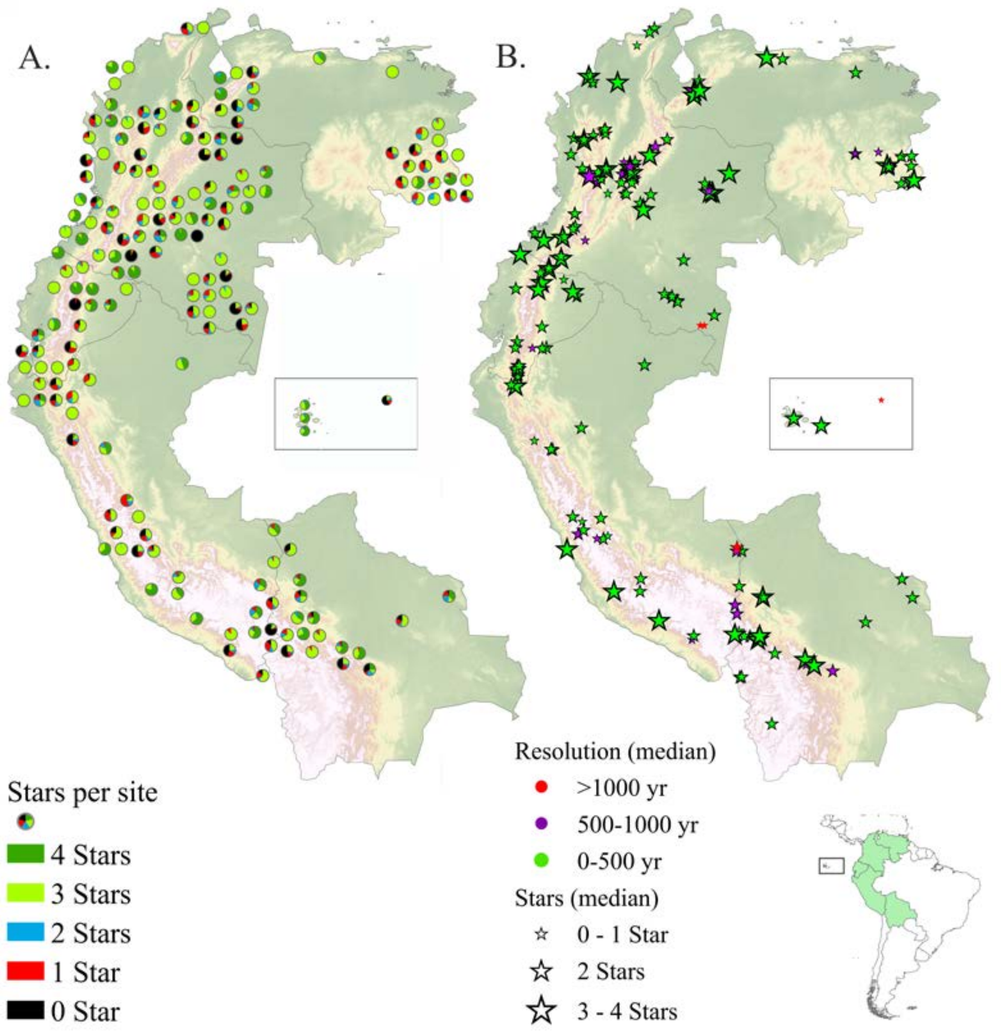

Figure 4. Histograms depicting the star classification outcome on sample level (A, C) and sites (B, D) for the last 60 kcal BP. Histograms A) and B) depict the MIS 3 (at 1000 yr time bins) and histograms C and D the last 25 kcal (at 500 yr bins). The height of the bar indicates the number of samples 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).

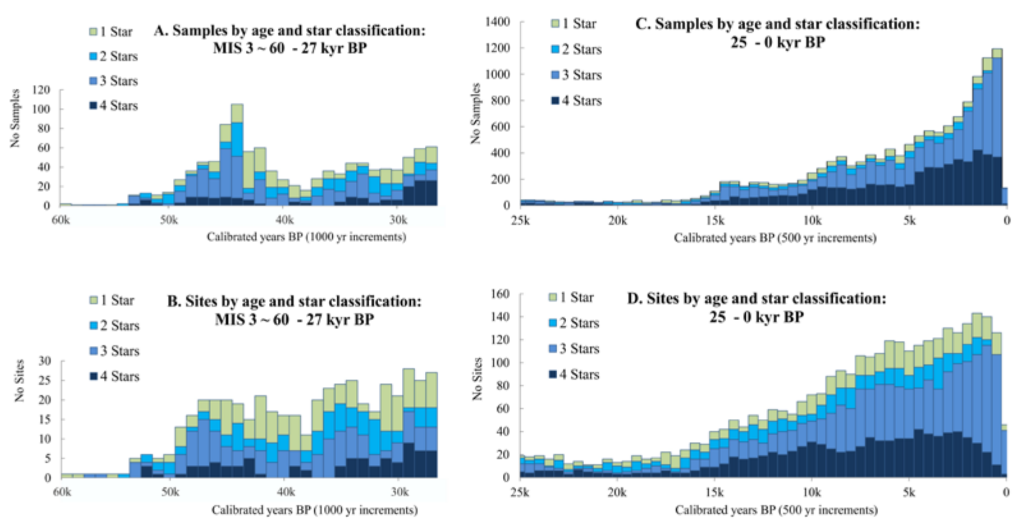

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Figure 5. Changing mean sample resolution (left) and mean number of stars (right) of the pollen database of northwest South America during the period 100 kcal to -50 cal yr BP.

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