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Interactive comment on "Climate variability and human impact on the environment in South America during the last 2000 years: synthesis and perspectives" *by* S. G. A. Flantua et al.

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Response to V. Iglesias (www.clim-past-discuss.net/11/C1576/2015/): Interactive comment on "Climate variability and human impact on the environment in South America during the last 2000 years: synthesis and perspectives" by S. G. A. Flantua, H. Hooghiemstra, M. Vuille, H. Behling, J. F. Carson, W. D. Gosling, I. Hoyos, M. P. Ledru, E. Montoya, F. Mayle, A. Maldonado, V. Rull, M. S. Tonello, B. S. Whitney, and C. González-Arango et al. doi:10.5194/cpd-11-1219-2015

We much appreciate the review report on our paper and we found it very helpful to address the different questions in more details. We have included nearly all suggestions

in the text and here we address each comment with explanation (indicated by »).

* The manuscript is well written (although it could largely benefit from proofreading and language revision) and the figures are clear.

» Before submitting, the final version will go through several revisions. Thank you for this suggestion.

1) I think the title is a little misleading. From its content, I would expect the manuscript to review multiple climate proxies (possible models as well), provide a synthesis and discuss how anthropogenic impact has altered the landscape. As opposed to this, the authors a) provide an overview of modern South American climate; b) attempt to reconstruct climatic variations in seven sub-regions of South America; c) describe some indicators of land-use.

» Thank you for this observation. We adapted the title to: Climate variability and human impact in South America during the last 2000 years: synthesis and perspectives from pollen records.

2) The climate overview is very good, concise and with enough details to avoid oversimplifications. I believe that it would be beneficial to include a short discussion of the similarities and differences of Figs 2 and 3, and 4 and 5, respectively. At the moment, those figures are always cited in pairs (i.e., 2 and 3, and 4 and 5), and the advantage of showing both correlation and regression is not obvious.

»We have added a short explanation regarding the similarities and differences between correlation and regression maps and now discuss in greater detail how they provide different and complementary information.

3) For analytical purposes, the authors divided South America in seven sub-regions and provided a characterization of their modern setting. Although climate is described in all cases, the text is somehow unbalanced in as much as, in some cases, geological data are reported and modern climate-vegetation relationships are parameterized,

while in other areas only a very superficial description of the dominant plant types is given. Whereas for this manuscript the geology of each sub-region might not be crucial, it might be important to discuss modern climate-vegetation relationships, at least, qualitatively.

» We agree that it is important that the regional descriptions are consistent but we also feel that different environmental variables might be more relevant in some records than others. Following the reviewer's suggestion, we will check on consistency and make the necessary adjustments to increase the overall readability of the manuscript. Thank you for this observation.

4) Pollen records from each sub-region are assessed in terms of their potential for climate reconstructions. Records are chosen according to very high standards (and I agree with the authors in that more flexible criteria could be applied). However, the authors state that, 'To use pollen as a palaeoclimate proxy, the degree of human impact on the vegetation needs to be considered minimum or absent over the last 2 ka' (p. 3840, lines 13-14). I believe that the minimum requirements for using pollen as a climate proxy are: a) vegetation needs to be assumed in equilibrium with climate (i.e., no disturbance –anthropogenic or natural-, no biotic interactions); b) the pollen-vegetation (land cover)-climate relationship needs to be calibrated and c) the existence of analytical and natural noise in the pollen time series needs to be taken into account (i.e., high frequency fluctuations do not necessarily represent changes in the landscape). Although requirement (b) can be (and has often been) relaxed -qualitative reconstructions are highly informative-, (a) and (c) cannot be ignored. In the literature, there are plenty of examples of ways in which these limitations can be overcome (compositing, Bayesian and frequentist models, use of plant functional types) and robust climate reconstructions achieved (eg, Peyron et al. 2000, Quaternary Research; Davis et al. 2003 QSR, Trondman et al 2015 Global Change Biology). My questions are: 4.1) Why are records with 'signs' of human impact discarded? Disentangling natural and anthropogenic drivers of environmental change is an extremely challenging task. As the

authors state 'Indirect indicators such as change in forest composition (e.g. due to deforestation) or species known as disturbance indicators (Cecropia and Mauritia) need additional proxies to derive conclusive findings. Only by looking at pollen changes in context with other evidence – e.g. charcoal, limnology, sedimentology, archaeology can the correct origin of these changes be identified.' (p. 3505, lines 5-10). I assume (and might be mistaken) that for most records there is no independent evidence of human impact (and, of course, absence of evidence is not evidence of absence). If that is the case, the climate reconstruction is likely to be biased towards sites with fewer proxies.

» Records with signs of human impact were not discarded. To clarify this issue, we added to p. 3505, line 11 the following explanation: "Ambiguous records with fewer proxies were not immediately discarded, but considered within the context of the other records from their wider region. Based on this, an assessment could be made as to whether an anthropogenic signal may have obscured natural vegetation change trajectory."

Additional comment from reviewer: Additionally, the discussion results a little contradictory in that decreased arboreal pollen, for instance (but the same is true for Cyperaceae, Asteraceae and Chenopodiaceae, among other taxa) is sometimes interpreted as anthropogenic deforestation and in other occasions is inferred to be a response to decreased moisture. I believe that perhaps a better approach would be to include all records, account for local-scale variability (see references above). They are a few of many examples of robust climate reconstructions in areas of long histories of intense human impact, such as Europe and Africa) and, when available, draw on the archeological record to test the assumptions of the chosen method.

Response$_{toV}Iglesias$

» Here we provide an answer to both 4.1 and 4.3 as they are similarly in context. Question 4.3 was: Why are the climate reconstructions based on the interpretation of the authors of the records (when the dangers of doing so are clearly pointed out in the manuscript) and not on some sort of synthesis/compositing/re-analysis?

» The reviewer presents an idealized set of criteria for the use of pollen as a climate proxy; and we agree that it is essential that our community strives for excellence in data collection for the pursuit of our research goals. These criteria, however, are unrealistic for South America, at least at this present time. The calibration of pollen to climate and/or land cover data (criterion 'b') requires good vegetation mapping, plant-pollen harmonization and well-resolved climate gauging data, much of which is unavailable for the existing modern pollen records from South America and varies greatly across the region (often associated with differences across political boundaries). At present, vegetation mapping is well-resolved by ecoregion (Olson et al., 2000), but these do not offer the spatial resolution necessary to understand climatic responses of individual taxa and/or to calibrate mechanistic pollen model for land cover reconstructions, as suggested by the reviewer. Pollen-plant harmonization is still under development in most ecosystems. For lake records especially, forest pollen taxa that can reflect a range of ecologically-distinctive vegetation formations (e.g., Moraceae/Urticaceae) often comprise a significant proportion of the signal, thus assigning a climatic or land cover value to these taxa is highly problematic, as is required by criterion 'b'. Despite these problems, the qualitative approach adopted by tropical palaeoecologists, in the absence of better calibration data, has provided valuable information on past vegetation and climate change in the tropics. (NB. The absence of 'better data' is an issue that we are striving to address as a community but it takes time. The modern pollen trap data from the Amazon, for example, is not 10 years in publication (Gosling et al. 2005, 2009).) In the absence of calibration data, tropical palaeoecologists rely on a combination of indicator taxa (or pollen types unique to specific biomes) and decades of ecological studies and plot-level surveys to understand plant-pollen relationships within the biomes in which they work. The more stringent criterion 'a', that vegetation needs to be assumed in equilibrium with climate, with no anthropogenic or natural disturbance, or biotic interactions, has been given serious consideration by the co-authors. Firstly, to require 'no biotic' interactions within a functioning ecosystem is simply an impossibil-

ity. Ecosystems by their definition are systems of energy transfer through interactions with the constituent biological components; this is true of ecosystems in any part of the globe, including temperate Europe where quantitative climate reconstructions have been achieved from pollen. These studies have been carried out, despite the long standing knowledge that soils, which have biotic components, have controlled post-glacial vegetation movement and changes in community composition. In the Amazon, the hydrological cycle on which the rainforest depends is in turn dependent on evapotranspiration of this prominent ecosystem. In this respect, biotic interactions cannot be discounted in the use of pollen, or any, biological proxy. Instead, it is far more realistic to argue that it is required that climate plays a significant role in controlling the biogeography of tropical ecosystems. Ecosystems of South America are in equilibrium with climate, but like so many biogeographic enquiries, the scale of the vegetation unit under study needs to be considered in the interpretation of pollen data. At continental scale, there are several biomes that occupy the same climatic space, but are differentiated by edaphic conditions. Savannas and seasonally-dry tropical forests, for example, require the same precipitation regime, but savannas occur on infertile soils. Similarly, hydrological savannas and rainforests might co-exist where there are differences in soil conditions. At a continental scale, therefore, plant distribution is controlled by climate, but soils exert a secondary level of control. Within each of the edaphically-controlled vegetation formation, however, climate can exert a control over community composition and vegetation structure, but to interpret the pollen records correctly requires a sound understanding of the ecological functioning of the ecosystem in question. The requirement to understand the unique functioning of several prominent tropical ecosystems is the reason we approached the study through multiple author collaboration and asked coauthors to make their own qualitative assessments of the records in their region, rather than attempting to compile datasets from across the continent and interpret them in a uniform way.

As well as edaphic conditions, anthropogenic impacts are another key non-climatic driver of vegetation change. Given that region-specific context is fundamental to sound interpretation for environmental reconstructions, we involved co-authors with expertise in specific regions who are best positioned to consider the drivers of vegetation. A criticism levelled by the reviewer is that anthropogenic deforestation and decreased moisture might result in similar signals in the pollen record. We accept this is a possibility and have highlighted these issues within the new version of the manuscript. An assessment was made of the records, based on the original authors interpretations, and those where the dominant driver of vegetation composition was likely anthropogenic impact, were deemed unsuitable for a reconstruction of climate-driven vegetation change. In this respect, 'sites with "signs" of human impact were not discarded', but are examples of how we controlled for non-climatic drivers of vegetation change through independent assessment of each record. Whether our approach is qualitative or quantitative, this independent assessment is required of each record to determine its suitability for climate reconstruction. Thus, by involving co-authors appraised of the contextual information (archaeological, ecological, geological, etc.) of each region, interpretations were made based upon all the available evidence; which included modern environmental information, plant-environmental interactions, archaeology, and additional proxy data. For the most part, pollen records contained additional proxy data to provide further support in determining the driver of vegetation change. However, given the availability of different types of contextual information, we disagree that 'the climate reconstruction is likely to be biased towards sites with fewer proxies'. The qualitative approach adopted to consider site context for each record, has allowed us to account for 'local scale' variability for each record, as suggested by the reviewer.

Another key issue that limits the development of a continental-scale quantitative model for climate reconstruction is the high degree of overlap in pollen types among biomes. Tropical palaeoecologists can often confidently link specific environmental or climatic conditions to a particular pollen type, but given the high degree of taxonomic overlap among different ecosystems and biomes, climatic reconstructions can be problematic if we are comparing like pollen-types (families) among ecologically-distinctive biomes. For example, to explore the ability to use pollen as a climate proxy, Punyasena (2008)

linked the spatial distribution of plant families (available from Gentry's forest plot data) pollen data from the LAPD, and restricted the taxonomic resolution to family level because this is the level to which most pollen is identified. A significant relationship between plant family and temperature and/or precipitation was found in the case of several families. In the application of the calibration dataset to fossil data, Punyasena et al. (2008) were successful at temperature reconstruction, but the model was incapable of reconstructing precipitation where there were taxonomically-similar forest formations that were tolerant of different flooding regimes (Whitney et al., 2011, Suppl. Info), as demonstrated by independent proxy data. In the case of high degree of taxonomic similarity at family level, a 'one size fits all' model has been demonstrated to give variable results.

Given the above constraints, we argue that it is unrealistic to apply a quantitative approach to reconstructing climate in the Neotropics at this time. Although the author list draws together some of the more experienced and published researchers from each region (able to comment on all the pollen studies in their region), there are several reasons why a quantitative reconstruction is not feasible. There simply are not enough calibration sites compared to Davis et al. (2003) and similar northern temperate reconstructions to produce sound calibration datasets. Land cover reconstructions, such as Trondman et al. (2015) require further data to modern pollen data, such as fall speeds and pollen productivity estimates, which have not be obtained for South America. (B.S. Whitney [pers. comm.] is currently calibrating mechanistic pollen models to Amazonian ecosystems but, due to data restrictions, has minimized the model to a forest/non-forest binary). Statistical tools are often highly prized and viewed as superior methods, but where there is limited calibration data, it is imprudent to push towards reconstructive models. The drive to provide quantitative values associated with climate change (however inaccurate) is neither wise nor necessary, especially given that statistical tools can only build upon, but cannot replace, sound ecological and context information for a given pollen record.

Additional references: Gosling, W.D., et al. (2005) Modern pollen-rain characteristics of tall terra firme moist evergreen forest, southern Amazonia. Quaternary Research, 64: 284-297

Gosling, W.D., et al. (2009) Differentiation between Neotropical rainforest, dry forest, and savannah ecosystems by their modern pollen spectra and implications for the fossil pollen record. Review of Palaeobotany and Palynology, 153: 70-85

Punyasena, S.W., et al. (2008). Quantitative estimates of glacial and Holocene temperature and precipitation change in lowland Amazonian Bolivia. Geology, 36(8):667

Punyasena, S.W. (2008) Estimating Neotropical palaeotemperature and palaeoprecipitation using plant family climatic optima. Palaeogeogr Palaeoclimat Palaeoecol, 265: 226-237

Whitney BS et al. (2011) A 45 kyr palaeoclimate record from the lowland interior of tropical South America. Palaeogeogr Palaeoclimat Palaeoecol, 307: 177-192. Supplementary Information.

4.2) Why is fire considered as anthropogenic disturbance?

» The reviewer poses a very general question that covers a wide topic extensively discussed in the literature. We are aware of the fact that fire is thought to be a transformative agent within tropical ecosystem, both as a result of human practices and natural climatic forcing. Conclusive evidence is more ambiguous further back in time, e.g. during postglacial times, but for many localities within our 2 ka review, fire is considered to be highly anthropogenic related. We follow the original interpretation of the authors about the possible causes of fires at each individual site. It is important to note, that the manuscript is solely based on climatic information derived from pollen records (excluding charcoal), thus the climate-human-fire feedbacks are not treated in depth.

The group of co-authors has published and supported a series of studies where the fire-human-relationship was evidenced by different proxies:

Behling, H., Hooghiemstra, H., 1998. Late Quaternary palaeoecology and palaeoclimatology from pollen records of the savannas of the Llanos Orientales in Colombia. Palaeogeography, Palaeoclimatology, Palaeoecology 139, 251–267.

De Porras, M.E., Maldonado, A., Abarzúa, A.M., Cárdenas, M.L., Francois, J.P., Martel-Cea, A., Stern, C.R., Méndez, C., Reyes, O. (2012). Postglacial vegetation, fire and climate dynamics at Central Chilean Patagonia (Lake Shaman, 44 S). Quaternary Science Reviews 50, 71–85.

Niemann, H., Behling, H., 2008. Late Quaternary vegetation, climate and fire dynamics inferred from the El Tiro record in the southeastern Ecuadorian Andes. Journal of Quaternary Science 23, 203–212. doi:10.1002/jqs.1134

Montoya, E., Rull, V., Nogué, S. (2011). Early human occupation and land use changes near the boundary of the Orinoco and the Amazon basins (SE Venezuela): Palynological evidence from El Paují record. Palaeogeography, Palaeoclimatology, Palaeoecology 310, 413–426. doi:10.1016/j.palaeo.2011.08.002

Montoya, E., Rull, V. (2011). Gran Sabana fires (SE Venezuela): a paleoecological perspective. Quaternary Science Reviews 30, 3430–3444. doi:10.1016/j.quascirev.2011.09.005

Iriarte, J., Power, M.J., Rostain, S., Mayle, F.E., Jones, H., Watling, J., Whitney, B.S., McKey, D.B. (2012). Fire-free land use in pre-1492 Amazonian savannas. PNAS 109, 6473–6478. doi:10.1073/pnas.1201461109

Additional relevant references: Bush, M.B., Silman, M.R., McMichael, C., Saatchi, S., 2008. Fire, climate change and biodiversity in Amazonia: a Late-Holocene perspective. Philosophical Transactions of the Royal Society of London B: Biological Sciences 363, 1795–1802. doi:10.1098/rstb.2007.0014

Marlon, J.R. 2013. Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. Quaternary Science Reviews 65, 5-25

Power, M.J., et al. 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics 30, 887–907. doi:10.1007/s00382-007-0334-x

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Thank you for your suggestions on our paper.

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