Polylepis woodland dynamics during the last 20,000 years

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Version: Accepted Manuscript

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1111/jbi.13209

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Valencia et al. *Polylepis* woodland dynamics during the last 20,000 years

Running title: *Polylepis* woodland dynamics

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Acknowledgements: This work was supported by the National Science Foundation grants EAR-1338694 and NSF-1624207.

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Article type: Synthesis, 02 Tables, 05 Figures
8678 words, including title page and references.
Abstract

Aim: To determine the paleoecological influences of climate change and human land use on the spatial distribution patterns of *Polylepis* woodlands in the Andes.

Location: Tropical Andes above 2900 m between 2 °S and 18 °S of latitude

Methods: Pollen and charcoal data were gathered from 13 Andean lake sediment records and were rescaled by the maximum value in each site. The rescaled pollen data was used to estimate a mean abundance and coefficient of variation to show woodland expansions/contractions and woodland fragmentation over the last 20,000 years. The rescaled charcoal was displayed as a 200-yr moving median using 500-year bins to infer the influence of fire on woodland dynamics at landscape scale. Pollen and charcoal were compared with speleothem, clastic flux and archaeological data to assess the influence of moisture balance, glacial activity and human impact on the spatial distribution of *Polylepis* woodlands.

Results: Woodland expansion and fire were correlated with precipitation changes and glacier dynamics from c. 20 to 6 kcal BP (hereafter thousands of calibrated years before present). Charcoal abundances between 20 and 12 kcal BP were less common than from 12 kcal BP to modern. However, human-induced fires were unlikely to be the main cause of a woodland decline centered at 11 kcal BP, as woodlands recovered from 10.5 to 9.5 kcal BP (about 2-fold increase). Charcoal peaks analogous to those that induced the woodland decline at 11 kcal BP were commonplace post-9.5 kcal BP but did not trigger an equivalent woodland contraction. An increase in the coefficient of variation after c. 5.5 kcal BP suggests enhanced fragmentation and coincided with the shift from logistic to exponential
growth of human populations. Over the last 1000 years, Polylepis became hyper-fragmented with over half of sites losing Polylepis from the record and with coefficients of variation paralleling those of glacial times.

Main conclusions: Polylepis woodlands formed naturally patchy woodlands, rather than a continuous vegetation belt, prior to human occupation in the Andes. The main factors controlling pre-human woodland dynamics were precipitation and landscape heterogeneity.

Human activity led to hyper-fragmentation during the last c. 1000 years.

Keywords: Andean forest, climate change, endemism, fossil pollen, Holocene, human impact, interglacial, natural fires, Polylepis woodlands, hyper-fragmented

1. Introduction

An abrupt decline in biodiversity and endemism coincides with the transition from upper Andean forest transitions to Puna grassland (Young, 1993; Young et al., 1999; Yensen & Tarifa, 2002; Körner, 2012). The exception to this pattern is in stands of Polylepis woodland, which grow as islands within the grassland. The Polylepis woodlands support a range of endemics that are habitat specialists, and other species that only occur at such high elevations in the shelter of the woodland. Consequently, Polylepis is disproportionately important to local and regional biodiversity (Fjeldså et al., 1999; Myers et al., 2000; Herzog et al., 2002; Chesser, 2004; Witt & Lane, 2009; Gareca et al., 2010). The important role of Polylepis in providing high-elevation habitat diversity led to Polylepis woodland being identified as a conservation priority throughout the tropical Andes (Fjeldså & Kessler, 1996; Fjeldså, 2002a; Servat et al., 2002; Young & León, 2007; Gareca et al., 2010).
Polylepis is a fire intolerant genus (Kessler, 2006; Cierjacks et al., 2008) that thrives in areas minimally impacted by human activities and grazing (Sylvester et al., 2014, 2017). Polylepis woodlands are present from Venezuela to northern Chile and Argentina, and can be formed by most of the 25 members of the genus (Simpson, 1979; Fjeldså & Kessler, 1996). The peak of biodiversity of other species associated with Polylepis woodlands occurs in Peru and Ecuador (Fjeldså, 2002b; Gareca et al., 2010; Lloyd et al., 2012). Polylepis can occur up to elevations of 5200 m (Ellenberg, 1958; Fjeldså & Kessler, 1996), making them the highest growing tree in the world. Although Polylepis is most commonly associated with the grassland (Puna), it can also grow below the treeline within the Andean forest; with some individuals occurring as low as 2000 m asl (Kessler, 2002).

Given the breadth of potential Polylepis habitat, Ellenberg (1958) suggested that the modern patchy distribution of woodland could be the product of human impacts instead of a natural distribution determined by microclimate conditions (Kessler, 2002). Ellenberg’s hypothesis gained acceptance based upon observations of the high degree of modern landscape modification through land-use change, fires, and wood extraction (Fjeldså, 2002b; Kessler, 2002). The patchy distribution of Polylepis was attributed to natural mechanisms such as fire and microclimate preferences that caused population disjunctions, which were later exacerbated by human activity (Simpson, 1979; Fjeldså, 2002b; Hensen, 2002; Kessler, 2002, 2006; Purcell & Brelsford, 2004; Gosling et al., 2009).

The last deglacial (25-21 thousands of calibrated radiocarbon years before present, henceforth kcal BP) was about 7-9°C cooler than today in the high Andes (Bush et al., 2004; Baker & Fritz, 2015). Andean deglaciation began c. 21 kcal BP and most glaciers had retreated to near modern limits by c. 13 kcal BP (Seltzer et al., 2002; Paduano et al., 2003;
Smith et al., 2008; Urrego et al., 2011). The deglacial warming was evident in an upslope movement of most floral elements, including *Polylepis*, between c. 20 kcal BP and 13 kcal BP (van der Hammen, 1974; Bush et al., 2004; Valencia et al., 2010; Groot et al., 2011). The largest climatic event of the Holocene period (11.7 kcal BP – modern) was a sequence of droughts mostly experienced between c. 9.5 kcal BP and 5 kcal BP (Bush & Gosling, 2012).

Lake levels fell during this time and landscapes became fire-prone (Cross et al., 2000; Mayle & Power, 2008). Mesic conditions returned after between 5 and 4 kcal BP, and by 3 kcal BP most lakes had attained their modern levels (Wolfe et al., 2001; Bush et al., 2005; Mayle & Power, 2008; Hillyer et al., 2009).

Terracing and irrigation for several millennia before European arrival provide compelling evidence that pre-Columbian cultures transformed many Andean landscapes through agriculture (Denevan, 2001; Covey, 2008; Isbell, 2008). The earliest archaeological evidence suggesting human occupation of the Andes dates c. 13 kcal BP (Dillehay et al., 2008; Rademaker et al., 2014) although coastal areas in the Pacific showed occupation evidence at c. 18 kcal BP (Dillehay et al., 2015). These data bring into question earlier assertions that humans could not have shaped Andean landscapes until c. 10-9 kcal BP (Aldenderfer, 2008; Sandweiss & Richardson, 2008; Rademaker et al., 2014). Moreover, models based on archaeological data show that the exponential phase of human population growth did not occur until 6-5 kcal BP (Goldberg et al., 2016). Whether the human colonists existed at sufficient density in the early-Holocene, or during the mid-Holocene, to cause wide frequency ecological change in the Andes remains to be investigated. Paleoecological reconstructions that predate the human incursion (taken to be c. 13 kcal BP) in the Andes can provide invaluable insights into the natural dynamics of *Polylepis* woodlands. Here we
synthesize data from 13 paleoecological records from the high Andes of Ecuador, Peru and Bolivia, to address a series of research questions:

1. Did Polylepis woodlands form a continuous belt at any time since the last glacial maximum at c. 21 kcal BP?

2. Did Polylepis woodlands contract due to human induced fires immediately after human arrival (i.e. 13 kcal BP, sensu Rademaker 2014) in the high Andes?

3. Did Polylepis woodland decline in concert with the growth of human populations?

2. Materials and methods

2.1 Study region

The region selected for study lies between 2°S and 18°S, occupies an elevation range from 2900-4150 m asl, and provides a representative overview of the geographic area occupied by Polylepis woodlands (Figure 1 and Table 1; Fjeldså & Kessler, 1996). This area excludes sites where Polylepis sericea Wedd. is distributed because this species is not found above treeline (Kessler, 2002). Mean annual temperatures range from c. 6-15 °C, with the differential between daytime maxima and night time minima exceeding 20 °C. Frost is most likely in the austral winter but could occur year round. Precipitation within the study region is seasonal with an austral summer wet season coinciding with the development of the South American Summer Monsoon (Zhou & Lau, 1998; Vuille & Bradley, 2000; Marengo et al., 2004). A gradient of modern precipitation exists with northern sites (e.g. Ecuador) receiving in excess of 1500 mm, while those in the Bolivian Altiplano receive just 400-700 mm per year (Hijmans et al., 2005).
2.2 Records of past environmental change

In this synthesis we review data from published lake sediment records of fossil pollen and charcoal sites (13 sites) above 2900 m a.s.l from 2-18 ºS (Table 1; Fig. 1 and 2). The palaeoenvironmental records obtained from the lake sediments provide a regional climate, vegetation, and fire history above the elevation of treeline (Hansen et al., 2003; Bush et al., 2005; Weng et al., 2006; Valencia et al., 2010, 2016; Williams et al., 2011).

Pollen and charcoal data were rescaled by the maximum value observed in each record to allow comparisons among sites (i.e. maximum abundance accounts for 100%, Fig. 2). The underlying assumption was that the maximum value observed in each site corresponded to the maximum woodland expansion or fire event that could be reached in each record. To allow for temporal comparisons, the pollen data from each site was interpolated at a resolution of 50 years and an average abundance across all sites in each time slice was calculated (i.e. landscape scale woodland abundance). This metric of Polylepis abundance across the landscape (presence at multiple sites) is hereafter referred as Polylepis landscape value (PLV). It should be noted that because sites deglaciated at different times, and hence were not all available to be colonized in every time-slice, the PLV was estimated using only the sites that were deglaciated within each specific time-slice. Furthermore, the estimation of the PLV and frequency for Polylepis excluded two sites (Siberia and Pacucha) where Polylepis could have been outcompeted by other arboreal species migrating upslope in the last 12 kcal BP (i.e. possible local natural-extinction; Appendix 1, Fig. S1). Thus the total number of sites that could have supported Polylepis in a given time slice varied from 4 to 13 (Fig. 2, 4a).
Charcoal data were rescaled, merged into one dataset, and were bootstrapped 1000 times using 5 observations per time to estimate a 200-year running median using 500-year bins (Fig. 2, Appendix 1 S2). The selection of number of observations (five) corresponded to the lowest observation number encountered in all the 500-year bins. Bins smaller than 500 years were avoided because they produced zero observations per bin while larger than 500 bins would reduce the temporal resolution. Boxplots were generated with the resampled data depicting the median (central line), interquartile range (IQR, boxes), 1.5*IQR above and below the IQR (whiskers).

A Bayesian correlation test was run using the PLV, charcoal medians, isotope and clastic data at 50-year resolution following the framework proposed by Liang et al., (2008) implemented in the R-package ‘BAYESMED’ (Wetzels & Wagenmakers, 2012, Table 2; Nuijten et al., 2015b). The Bayes factor (BF) in the analysis provides support for correlation when BF >1, no correlation when BF=1 and support against correlation when BF <1. The correlations were run for a period where data are available for all the proxies (Fig. 3) excluding the period younger than 6.15 kcal BP as no data were available for the Santiago isotope record (Mosblech et al., 2012). A Spearman rank correlation test run in R plotted with the R-package ‘CORRPLT’ (Wei & Simko, 2016) was consistent with the Bayesian correlation (Appendix 1, Fig. S3). Note that the oxygen isotope data ($\delta^{18}O$) is a proxy that registered changes in precipitation (Mosblech et al., 2012; Cheng et al., 2013) and the carbon isotopes ($\delta^{13}C$) changes in lake level (Baker et al., 2001b). Both isotopes ($\delta^{18}O$ and $\delta^{13}C$) became enriched during dry periods (e.g. E-HDE in Fig. 3). The clastic sediment flux (Fig. 3e) is a proxy that recorded glacial dynamics. The clastic sediment flux had high values during periods of enhanced glacial activity.
To determine the degree of site similarity among the Andean landscape, a coefficient of variation (CV; standard deviation divided by the mean*100) was calculated and used as a fragmentation indicator. The CV would take the highest values during periods where *Polylepis* is abundant in some sites and low (or locally extinct) in others (i.e. patchy landscape). On the other hand, the CV would be zero if *Polylepis* was equally abundant in all the sites within the same time window. The CV was calculated based on the rescaled pollen data (50-year resolution). Note that the CV can take multiple values even when the PLV remains constant.

All the data were analyzed and plotted against age using R (R Development Core Team, 2014).

### 3. Results

The rescaled abundances of *Polylepis* pollen had time transgressive peaks across each of the 13 sites during the last c. 20 kcal BP (Fig. 2). Similarly, the charcoal records showed a broad tendency for increasing fire-frequency between the onset of the record and the mid-Holocene, with less predictable trends in the late Holocene. The 13 sites appear to be broadly divided between those containing *Polylepis* in the deglacial period from those that had primarily Holocene peaks of occupation. Those with Pleistocene occupation peaks can be further subdivided by elevation into a high (K homer K hocha, Caserococha, Compuerta) and a low group (Refugio, Chochos, Llaviucu, Pacucha, Siberia) separated by about 550 m vertically (Fig. 2).

*Polylepis* landscape values, whether amalgamated or treated as low, mid, and high elevation groups, were all negatively correlated with charcoal and positively correlated with...
clastic flux, which can be taken as a proxy for glacial outflow (Fig. S4 and S5). As our primary question addresses patch occupancy where *Polylepis* occurs at any given time in the past, we use the amalgamated PLV value, as its calculation is elevation-independent. Values for *Polylepis* landscape value (PLV) ranged from 13 to 60% during the last c. 20 kcal BP (Fig. 3a). PLV was consistently higher than 25% from c. 20 to 12 kcal BP, dipped to c. <20% at 12-10 kcal BP, but was predominantly above 20% the last c. 10 kcal BP (c. 26% on average). Between c. 20 and 6.2 kcal BP the Bayes factor was consistently >100 and provided very strong evidence for correlation between *Polylepis* abundances (PLV) with isotopic, clastic-flux and charcoal data (sensu Nuijten et al., 2015a, 2015b; Fig. 3 & Table 2). The PLV is lowest (<20%) between 12-10 kcal BP when enriched δ¹⁸O (< -5‰) in nearby speleothems, and high charcoal abundances (>33%) in lake sediments, indicate an early Holocene Dry Event (E-HDE) (Fig. 3). Pollen abundances (PLV) remained > 20% after 9.5 kcal BP and did not decline during the mid-HDE phase 9.5 - 5 kcal BP indicated by charcoal values >45%. The charcoal abundances indicated an additional period of outstanding fire activity (values > 50%) during the last c. 2 kcal BP. The mid-HDE also saw a halving of the number of sites where *Polylepis* was documented and the onset of major civilizations in the High Andes. The coefficient of variation (CV; dimensionless), a proxy for fragmentation, increased after c. 5.5 kcal BP but the trend was steeper during the last two millennia increasing from 1.2 to 1.8 units. The magnitude of fragmentation recorded over the last millennia was analogous to that of the early deglacial time, i.e. from c. 20 to 17 kcal BP, when CV was >1.2 units (Fig. 4).

4. Discussion
4.1 *Polylepis* woodland cover prior to human occupation

For over half a century it has been debated whether the modern patchy distribution of *Polylepis* woodlands was natural, or the result of anthropogenic activities that fragmented what once was a larger-than-present and continuous woodland belt along the Andes (Ellenberg, 1958; Lauer, 1981). Furthermore, it was suggested that following human arrival (c. 12.8 kcal BP), *Polylepis* woodlands could have been easily eradicated by frequent fires (Renison et al., 2002; Cierjacks et al., 2008). Like modern humans who use fire for land management, small groups of early hunter-gatherers may have transformed large areas of forest using fire (Veblen et al., 1987; Kessler, 2002). Such a downturn in woodland cover soon after human arrival has not been tested in the light of evidence for a late Pleistocene human presence in the Andes (Rademaker et al., 2014).

Our analysis revealed that landscape scale *Polylepis* abundance, as indicated by PLVs, was positively correlated with inferred precipitation from speleothems between c. 20 and 6.2 kcal BP (Fig. 3, Table 2). This relationship suggests that the woodland dynamics were influenced by precipitation changes over >13,000 years. Clastic fluxes (Rodbell et al., 2008) were also in phase with the PLVs and isotopic data suggesting that either temperature and precipitation were negatively correlated or that precipitation played a major role controlling glacial extent in the Andes (Thackray et al., 2004; Rodbell et al., 2008; Shakun et al., 2015).

Following an early deglaciation onset in the Andes, the period between c. 20 and 17 kcal BP (Figs. 3 and 4) was still characterized by glaciated landscapes and no human influence (Seltzer et al., 2002). The PLVs (<50%) and CVs (1.5 - 2) showed that *Polylepis*
woodlands were very patchy, and charcoal abundances indicate fire events were rare. After 17 kcal BP, Polylepis woodlands expanded reaching a maximum cover from c. 17 to 14 kcal BP (c. 42-60%, Fig. 3a) and CVs were lower (1 - 1.1). Although mesic conditions characterized the period between c. 20 and 14 kcal BP, the time interval between c. 18 and 14 kcal BP was wetter than between c. 20 and 18 kcal BP as indicated by the δ^{18}O and clastic flux data (Baker et al., 2001b; Rodbell et al., 2008; Mosblech et al., 2012; Cheng et al., 2013). These observations were consistent with the formation of paleolakes in the Altiplano inferred from natural gamma radiation and isotopic analysis on carbonate deposits and coincided with the maximum woodland expansion (Baker et al., 2001a; Blard et al., 2011). Given the limitations of current temperature reconstructions for the Neotropics (Baker & Fritz, 2015; Shakun et al., 2015) the role of temperature modulating PLVs could not be evaluated in detail. The PLV maxima from c. 17 to 14 kcal BP could have being favored by an upslope Polylepis migration as temperature rose.

**The distribution of sites containing Polylepis in the deglacial period appears to support an initially split representation, with one set of sites at high elevation, i.e. 3950-4200 m, and another set of sites further downslope at c. 2800-3400 m. The intermediate elevation set of sites gain Polylepis representation in the Holocene, though it needs to be noted that only two of them have Pleistocene-aged sequences. Tentatively, we infer that the high- and low-elevation groups represent may represent two different niches, one being close to the ice front, and the other in a puna or super-puna landscape. The modern ecology of Polylepis includes species that occupy such habitats, such as the high-elevation specialist *P. tarapacana*, which today is found in very dry settings in Bolivia. That *P. tarapacana* can survive at 5200 m elevation in modern climates (Rada et al., 2001) shows that this genus is**
adapted to extreme cold, but we consider it unlikely that it was this species represented in these wetter Peruvian settings (Baker et al., 2001b; Hillyer et al., 2009). A species of *Polylepis* that lived close to the ice margin was apparently lost from these records with Holocene warming. The *Polylepis* representation of the lower slopes also wanes as representation in the mid-elevation sites increases, potentially indicating an upslope migration due to warming. The loss of *Polylepis* from the lower edge of its Pleistocene range would be expected as Andean forest moved upslope, probably outcompeting *Polylepis* below treeline. Again, we caveat this observation and note that *Polylepis* would undoubtedly have been responding to warming, but other factors such as the interaction between fire and topography (Valencia et al., 2016), the loss of megafauna (Rozas-Dávila et al., 2016), and changes in precipitation (Gosling et al., 2009) could have contributed to the observed pattern.

The strong evidence for correlation between isotopic data, clastic flux, PLV (woodlands) and charcoal depicted in Table 2 suggested that fires and human activity were unlikely to have constrained *Polylepis* abundance prior to 6.2 kcal BP. Although a correlation does not imply causation, it was more likely that climate (isotopic and clastic data as proxies for precipitation and temperature) modulated fire and woodland cover than the other way around (i.e. fire or woodland cover modulating precipitation and temperature).

### 4.2 Did *Polylepis* woodlands form a continuous belt at any time since the last glacial maximum (c. 21 k BP)?

*Polylepis* woodlands covered larger areas prior to human incursion than anytime after c. 12.8 kcal BP. The PLV (Fig. 3a) showed that the *Polylepis* woodland cover was
consistently higher from 20 to 12.8 kcal BP (30-60%) than any time after 12.8 kcal BP (usually <30% and c. 25% on average). During the period between c. 17 and 14 kcal BP, Polylepis was twice as abundant (c. 50% on average) as the post c. 12.8 kcal BP average.

Given the average abundance (c. 50%) and that all nine available records contained Polylepis, we infer that the genus attained its maximum abundance of the last 20,000 years between c. 17 and 14 kcal BP. Despite this abundance between c. 17 and 14 kcal BP, it is unlikely that a continuous woodland belt ever formed. The PLV (woodland cover) did not exceed c. 60%, suggesting that regardless of the Polylepis abundance; the local woodland cover was still patchy. The patterning of Polylepis distribution within each catchment, however, has yet to be resolved.

Landscape heterogeneity probably played an important role in controlling local woodland distribution (Valencia et al., 2016) interacting with the constant flux of climate that promoted local vegetation instability and therefore constrained the potential dominance of any given species (Hutchinson, 1957; Phillips et al., 2006; Killeen et al., 2007; Garreaud, 2009; Valencia et al., 2016). Our pollen-based evidence that Polylepis woodlands did not form a continuous cover is consistent with genetic studies on Polylepis tarapacana, which suggested the presence of larger, but disjunct, populations of this species during the Pleistocene than in the Holocene (Peng et al., 2015). Consequently, our inference of discontinuous Polylepis woodlands along the Andes during the terminal Pleistocene does not support the hypothesis that Polylepis formed a continuous woodland belt in the Late Pleistocene or Holocene sensu Ellenberg (1958).
4.3 Did *Polylepis* woodlands contract due to human-induced fires immediately after human arrival in the high Andes?

Humans are now known to have inhabited the high Andes by c. 12.8 kcal BP (Rademaker et al., 2014). The PLV showed that woodland cover declined from c. 13 to 10.5 kcal BP. A threshold of increased charcoal abundance is found at many sites during this time period. Increased fire frequency and human arrival were closely related in Africa, Australia, and potentially in the Andes (Roebroeks & Villa, 2011; Berna et al., 2012).

Occasional fire was clearly present in the Andes long before human presence (Hanselman et al., 2011), but the regular occurrence of fire may be taken as a much stronger indication of human activity. Though unsupported by archaeological data, we suggest that the regular occurrence of fire at c. 15 kcal BP (Fig. 3d) may have been caused by human activity. The increase in fire activity and the synchronous woodland decline was more intricate than a straight cause-effect interaction. Although humans became the most probable ignition agent when they arrived in the Andes, fires were most likely to be recorded during dry times when fire intensity, frequency and spread would be larger compared with those observed during wet periods (Bush et al., 2008; Cochrane & Ryan, 2009).

Simple explanations of increased human activity generating fires that caused the *Polylepis* decline (c. 12-10 kcal BP) run into difficulties in the early Holocene. Between c. 10.5 and 9.5 kcal BP, while fires were still frequent, the *Polylepis* woodland coverage expanded by a factor of 2.5. This woodland recovery also took place when it was estimated that the human population experienced its steepest pulse of logistic growth (Fig. 4b). Human population size in the Andes at this time is not known, but is assumed to have been at relatively low densities (Goldberg et al., 2016). This understanding suggests that the
influence of humans was unlikely to have been large enough to have caused the *Polylepis* woodland contraction prior to c. 5-6 kcal BP. Given that modern *Polylepis* pollen counts are higher today that at 10 kcal BP in many lakes, attributing the *Polylepis* decline to humans would also imply that the impact of the early hunter-gatherers was larger than that of modern land use. The most parsimonious explanation of variations in *Polylepis* woodland cover prior to c. 5-6 kcal BP is that Andean systems changed at the onset of the Holocene, becoming fire-prone as in previous interglacials (Hanselman et al., 2011). We infer that most of the early-Holocene woodland contraction was influenced by declining precipitation (Fig. 3 b-c) that induced the PLV decline after c.15 kcal BP (Fig. 3a). Although the fire trend was exacerbated by human arrival, the similarity of the PLV and precipitation curves until c. 5 kcal BP suggests that human activity only exceeded climatic controls after this point.

4.4 Did *Polylepis* woodland decline in concert with the growth of human populations?

The turning point of the mid-Holocene dry event in the Peruvian Andes that led toward wetter conditions at c. 5.5 kcal BP, coincided with the estimated onset of exponential human population growth (Goldberg et al., 2016). Previously, though human populations had been growing they were not transforming landscapes to the point where local *Polylepis* extinction occurred (e.g. Fig. 2, Siberia). A lack of extinction does not imply that humans produced no effect. We hypothesize that fires and land use would have affected *Polylepis* populations, but that landscape heterogeneity and rescue effects (sensu Brown & Kodric-Brown, 1977) allowed metapopulations to come and go, but led to overall woodland
persistence particularly in inaccessible areas (Levins, 1969; Sylvester et al., 2014, 2017; Valencia et al., 2016).

The transition from logistic to exponential growth in human population between 6 and 5 kcal BP (Goldberg et al., 2016) was reflected in increased reliance on agriculture, and settlements becoming permanent. The continuous pressure exerted by humans on a landscape prevented woodland re-colonization and led to a decline in Polylepis occurrence across sites. Consequently, readily accessible sites for human occupation exhibited an earlier loss of Polylepis than ones that were inaccessible. For example, the loss of Polylepis around Lake Pacucha occurred c. 10 kcal BP, whereas rugged and inaccessible sites at a similar elevation, such as Lake Chochos, retained its Polylepis until c. 6-7 kcal BP (Valencia et al., 2016). This contrasting pattern of human induced exploitation (locally extinct or near absent in some sites and abundant in inaccessible places) led to the formation of hyper-fragmented woodlands depicted by the increasing coefficients of variation (Fig. 4c), i.e. fragmentation of populations that already had a patchy distribution. Because Polylepis woodlands were able to thrive in the early Holocene, a period characterized by droughts, a woodland expansion in the last 4000 years would be expected. At the largely unimpacted sites of Miski and Huamanmarca (Fig. 2) Polylepis has indeed become more abundant in the late Holocene. This pattern, however, is not registered at sites with strong human influence. The increasing coefficient of variation over the last c. 4 kcal BP, strongly suggests increasingly heterogeneous landscapes consistent with a gradual hyper-fragmentation Polylepis woodland (i.e. fragmentation of populations that already had a patchy distribution). Moreover, the largest Polylepis woodland contraction started between c. 2 - 1 kcal BP (Fig. 3a) coinciding with the onset or development of high Andean civilizations such as Wari,
Tiwanaku, and Inca (Isbell, 2008). Over this period, the hyper-fragmentation of *Polylepis* woodlands became enhanced. The loss of woodland cover and resulting vegetation mosaics reduced *Polylepis* abundance to levels not seen since the early deglacial period (e.g. prior to c. 17 kcal BP; Figs. 4a, c, and d). Our data strongly suggest that human activities significantly reduced *Polylepis* woodland cover and abundance during the last 1000 years. Pre-Columbian civilizations were known to have enforced agroforestry and the protection of Andean woodlands (Chepstow-Lusty & Winfield, 2000), driven by woodland shortage in their occupied landscapes. Although these practices may have been successful preventing the local forest clearance, the *Polylepis* woodland decline showed that deforestation at landscape scale was commonplace.

5. Conclusions:

The spatial distribution of *Polylepis* derived from 13 paleoecological reconstructions was estimated for the last 20 kcal BP. *Polylepis*-rich systems showed an upslope migration response at the end of the last ice age. *Polylepis* woodlands reached their maximum expansion between c. 17 and 14 kcal BP prior to human arrival in the Andes. However, these woodlands were always patchy (i.e. maximum PLV of 60 %) and did not form a continuous woodland belt over the last 20 kcal BP. The most important factors controlling the *Polylepis* woodland dynamics prior to c. 6.2 kcal BP were precipitation and landscape heterogeneity. A combination of high precipitation, low temperatures, limited flammability, low biomass (fuel load) and rare ignitions led to fire being relatively rare before c. 13 kcal BP compared with the following period. As landscapes became warmer, drier, and humans more abundant, fire became a more regular component of Andean systems. Fire sensitive
taxa, such as *Polylepis*, were negatively affected by these changes. Of all these drivers, precipitation appears to have exerted such a strong influence that it could offset other trends in the early Holocene. This capacity, however, was lost as human populations grew in the late Holocene.

Our study suggests that although *Polylepis* has a naturally patchy distribution this pattern has been exacerbated over the last few millennia by human activities, a process that we identify as hyper-fragmentation. Reduced gene flow under modern hyper-fragmentation is potentially so limited that it may further compromise the long-term persistence of this genus under the ongoing effects of climate change.

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Polylepis woodland dynamics


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**Polylepis** woodland dynamics


**Biosketch: Bryan G. Valencia** is a palaeoecologist working as a postdoctoral researcher at the Florida Institute of Technology. He is investigating plant community responses to past climate change in South American high-Andean ecosystems. His research is focused on disentangling the human-climate influences on Neotropical plant communities using a multy-proxy approach.

**Author contributions:** B.G.V., M.B.B., W.D.G. conceived the ideas; B.G.V., M.B.B., and E.O. collected the data; B.G.V. analyzed the data; B.G.V. led the manuscript writing.
M.B.B., A.L.C., E.O., and W.D.G. made significant comments to the data analysis and manuscript writing.
Table 1. List of the studied sites displayed on Fig. 1 by latitude (southward) as reported in the original publications. The proxies evaluated per site were pollen (Po), charcoal (Ch), clastic deposition (Cl), oxygen isotopes (δ\(^{18}\)O), and carbon isotopes (δ\(^{13}\)C). Pollen and charcoal data from the marked sites (*) were transformed and analyzed to produce Fig. 2, 3, and 4).

<table>
<thead>
<tr>
<th>Lake or Speleothem (s)</th>
<th>Age (kcal BP)</th>
<th>Lat.</th>
<th>Long.</th>
<th>Proxies</th>
<th>Elev. m a.s.l</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chorreras Valley (highest lake)</td>
<td>c. 15.8</td>
<td>-2.75</td>
<td>-79.14</td>
<td>Cl</td>
<td>4020</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>Pampiada</td>
<td>c. 14.8</td>
<td>-2.76</td>
<td>-79.26</td>
<td>Cl</td>
<td>4100</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>*Chorreras</td>
<td>c. 17.7</td>
<td>-2.77</td>
<td>-79.16</td>
<td>Po, Ch, Cl</td>
<td>3700</td>
<td>Hansen et al., 2003; Rodbell et al., 2008</td>
</tr>
<tr>
<td>Pallcacocha</td>
<td>c. 15.0</td>
<td>-2.77</td>
<td>-79.23</td>
<td>Cl</td>
<td>4060</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>*Llaviucu</td>
<td>c. 16.7</td>
<td>-2.84</td>
<td>-79.14</td>
<td>Po, Ch, Cl</td>
<td>3150</td>
<td>Hansen et al., 2003; Rodbell et al., 2008</td>
</tr>
<tr>
<td>Santiago (s)</td>
<td>&gt;20.0</td>
<td>-3.01</td>
<td>-78.13</td>
<td>δ(^{18})O</td>
<td>980</td>
<td>Mosblech et al., 2012</td>
</tr>
<tr>
<td>El Condor (s)</td>
<td>&gt;20.0</td>
<td>-5.93</td>
<td>-77.30</td>
<td>δ(^{18})O</td>
<td>860</td>
<td>Cheng et al., 2013</td>
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<tr>
<td>*Compuerta</td>
<td>&gt;20.0</td>
<td>-6.91</td>
<td>-78.60</td>
<td>Po, Ch</td>
<td>3950</td>
<td>Weng et al., 2006; Bush et al., 2005; Rodbell et al., 2008</td>
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<td>*Chochos</td>
<td>c. 15.4</td>
<td>-7.63</td>
<td>-77.47</td>
<td>Po, Ch, Cl</td>
<td>3285</td>
<td>Hansen et al., 1995; Rodbell et al., 2008</td>
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<tr>
<td>*Baja</td>
<td>c. 18.2</td>
<td>-7.69</td>
<td>-77.53</td>
<td>Po, Ch, Cl</td>
<td>3575</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>Queshque</td>
<td>c. 18.4</td>
<td>-9.81</td>
<td>-77.30</td>
<td>Cl</td>
<td>4275</td>
<td>Rodbell et al., 2008</td>
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<tr>
<td>Huarmicocha</td>
<td>c. 17.3</td>
<td>-10.42</td>
<td>-76.83</td>
<td>Cl</td>
<td>4670</td>
<td>Rodbell et al., 2008</td>
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<tr>
<td>Junin</td>
<td>c. 42.2</td>
<td>-11.00</td>
<td>-76.10</td>
<td>Cl</td>
<td>4000</td>
<td>Rodbell et al., 2008</td>
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<tr>
<td>*Miski</td>
<td>c. 12.7</td>
<td>-13.02</td>
<td>-72.37</td>
<td>Po, Ch</td>
<td>3800</td>
<td>Valencia et al., 2016</td>
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<tr>
<td>*Huamanmarca</td>
<td>c. 12.7</td>
<td>-13.03</td>
<td>-72.37</td>
<td>Po, Ch</td>
<td>3900</td>
<td>Valencia et al., 2016</td>
</tr>
<tr>
<td>*Refugio</td>
<td>c. 19.5</td>
<td>-13.09</td>
<td>-71.70</td>
<td>Po, Ch</td>
<td>3389</td>
<td>Urrego et al., 2011</td>
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<tr>
<td>*Pacucha</td>
<td>&gt;20.0</td>
<td>-13.60</td>
<td>-73.32</td>
<td>Po, Ch</td>
<td>3090</td>
<td>Valencia et al., 2010</td>
</tr>
<tr>
<td>*Caserococha</td>
<td>c. 26.2</td>
<td>-13.65</td>
<td>-71.29</td>
<td>Po, Ch, Cl</td>
<td>3975</td>
<td>Paduano 2001; Rodbell et al., 2008</td>
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<tr>
<td>Pacococha</td>
<td>c. 14.4</td>
<td>-13.95</td>
<td>-70.88</td>
<td>Cl</td>
<td>4925</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>*Titicaca Taypi Chaka Khota</td>
<td>c. 13.5</td>
<td>-16.20</td>
<td>-68.35</td>
<td>Cl</td>
<td>4300</td>
<td>Rodbell et al., 2008</td>
</tr>
<tr>
<td>*Khomer Kocha</td>
<td>c. 18.1</td>
<td>-17.27</td>
<td>-65.73</td>
<td>Po, Ch</td>
<td>4150</td>
<td>Williams et al., 2011</td>
</tr>
<tr>
<td>*Siberia</td>
<td>&gt;20.0</td>
<td>-17.83</td>
<td>-64.72</td>
<td>Po, Ch</td>
<td>2920</td>
<td>Mourguiart et al., 2003</td>
</tr>
</tbody>
</table>
Table 2. Correlation of climate proxies with *Polylepis* PLV. There is a strong evidence for correlation between all the variables (i.e. Bayes factor was >100 for all the comparisons).

Note that the negative correlation coefficient between PLV and the isotopic data ($\delta^{18}O$ and $\delta^{13}C$) implies a positive correlation of PLV with inferred precipitation (e.g. Fig. 3a-c and 3f). The datasets used are proxies for enhanced glacial activity (clastic flux), fire activity (charcoal), precipitation ($\delta^{18}O$ from Condor and Santiago speleothems), and lake level ($\delta^{13}C$ from Lake Titicaca). Dataset details are depicted in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Clastic flux</th>
<th>Charcoal $\delta^{18}O$ vs BPDB</th>
<th>Condor $\delta^{18}O$ vs BPDB</th>
<th>Santiago $\delta^{18}O$ vs BPDB</th>
<th>Titicaca $\delta^{13}C$ vs PDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>-0.9149</td>
<td>0.8507</td>
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<tr>
<td>Condor</td>
<td>-0.8295</td>
<td>0.6680</td>
<td>0.7184</td>
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<td></td>
</tr>
<tr>
<td>Santiago</td>
<td>-0.7485</td>
<td>0.7904</td>
<td>0.6571</td>
<td>0.3960</td>
<td></td>
</tr>
<tr>
<td>Titicaca</td>
<td>-0.7388</td>
<td>0.8078</td>
<td>-0.7664</td>
<td>-0.8212</td>
<td>-0.6589</td>
</tr>
</tbody>
</table>
Figure 1. Map depicting the location of sites providing the pollen, charcoal, clastic flux and speleothem records used in this review (details in Table 1).
**Figure 2.** Pollen and charcoal abundances of selected sites plotted from high (top) to low elevation (bottom) against time depicted in thousands of years (kcal BP). Pollen (grey silhouettes) and charcoal (black bars) abundances were rescaled by the maximum value in each site (relative abundance) observed over the last 20 kcal BP. Periods where sites were covered in ice are marked with (*). Vertical lines depict the low, mid, and high elevational site grouping.
**Figure 3.** A comparison of *Polylepis* representation with proxies for climate change. (a) *Polylepis* landscape value (PLV) depicts the average across sites of the proportion of maximum cover of woodland at each individual site (Table 1). (b) Isotopic $\delta^{18}$O from Santiago (Mosblech et al., 2012) and (c) El Condor records (Cheng et al., 2013). (d) Charcoal 200-yr running median using 500-year bins (Table 1). (e) Glacial dynamics for the Andes inferred from detrital clastic material (Rodbell et al., 2008). (f) Isotopic $\delta^{13}$C of sedimentary organic content from Lake Titicaca. Labels and arrows on top of each diagram show the inferred estimate for each proxy (I.). The early Holocene Dry Event (E-HDE) and mid-Holocene dry event (M-HDE) were depicted by horizontal gray bands. The horizontal dashed line shows the earliest known archaeological evidence for the high Andes (Rademaker et al., 2014; Goldberg et al., 2016).
Figure 4. A comparison of Polylepis woodland representation with human population size estimation and spatial woodland-cover patterns. (A) Depicts the Polylepis average abundance (PLV, solid green line) weighted by the number of available sites (solid black line). The PLV (solid green line) and site number (solid black line) excluded the lowest sites Siberia and Pacucha over the last 12 kcal BP as Polylepis could have been naturally outcompeted by other arboreal taxa. The dashed green line (PLV) and the dashed black line (number of sites) represent the PLV and number of sites when Siberia and Pacucha are not excluded in the analysis over the last 12 kcal BP. (B) Logistic (red) and exponential (blue) best-fit growth models for human populations in the Andes (Goldberg et al., 2016). The models were based on probability density of summed calibrated radiocarbon dates. (C) Coefficient of variation for Polylepis pollen abundances. (D) Conceptual model for
landscape patchiness. Note that green solid circles depict the maximum cover that can be attained at each site and empty dashed circles sites that were covered in ice.
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### Polylepis landscape value (%)

- Number of sites: 5, 7, 9, 11, 13

### Human population size

- Density: 0.0, 0.1, 0.2, 0.3, 0.4

### Coefficient of variation

- 0.5, 1.0, 1.5, 2.0

### Landscape patchiness scenarios

- Hyper-fragmented
- Patchy
- Locally extinct
- Covered in ice

- Exponential: \( r = 2.31 \times 10^{-4} \)
- Logistic: \( K = 0.185, r = 1.32 \times 10^{-3} \)

- Probability density of summed calibrated radiocarbon dates

### Woodland cover per site

- Exponential
- Logistic

### Age (KBP)

- 0, 20, 40, 60
Figure S1. The *Polylepis* modern cumulative occurrence expressed as percent as function of elevation. Sites are depicted as dots and the treeline range is depicted as a grey bar between 3300 and 3500 m. To minimize the possible effects of competition replacing *Polylepis* at its lower distribution end, the two lowest sites (i.e. Siberia and Pacucha) were excluded from the analysis post 12 kcal BP when their abundances were still above zero. *Polylepis* pollen abundances were consistently present throughout the Holocene in Llaviucu (aka Surucucho) and Chochos and were included in the analysis.
Fire abundance sensu Power et al., (2008, 2010) provide results entirely consistent with charcoal analysis. However, this package was not used because (i) after data normalization the position of true zero values are not displayed, and (ii) composite score units are difficult to understand.

The increasing charcoal abundance departing from values close to zero indicate the shift from puna/paramo grasslands to shrubland and forest. This process was observed and indicated in the original publications.
Figure S3. Spearman rank correlation matrix of variables from Fig. 3A. The Spearman rho coefficients are depicted in red (negative correlation) and blue (positive correlation). All the correlations were significant $p<0.05$. 
Figure S4. A comparison of Polylepis representation with proxies for climate change as in Fig. 3 where the Polylepis and charcoal data were winnowed into high (Khomer Khocha, Caserococha, Compuerta), mid (Huamanmarca, Miski, Titicaca, Chorreras, Baja), and low (Refugio, Chochos, Llaviucu, Pacucha, Siberia) groups based on abundances depicted in Fig. 2. (a) Polylepis landscape value (PLV) depicts the average across sites of the proportion of maximum cover of woodland at each individual site (Table 1). a-high, a-mid and, a-low represent are similar to: (a) but estimated for high, mid and low groups. (b) Isotopic δ¹⁸O from Santiago (Mosblech et al., 2012) and (c) El Condor records (Cheng et al., 2013). (d) Charcoal 200-yr running median using 500-year bins (Table 1). d-high, d-mid and, d-low are similar to (d) but estimated for high, mid and low groups (no observations in the sliding window produced gaps). (e) Glacial dynamics for the Andes inferred from detrital clastic material (Rodbell et al., 2008). (f) Isotopic δ¹³C of sedimentary organic content from Lake Titicaca. Labels and arrows on top of each diagram show the inferred estimate for each proxy (I). The early Holocene Dry Event (E-HDE) and mid-Holocene dry event (M-HDE) were depicted by horizontal gray bands. The horizontal dashed line shows the earliest known archaeological evidence for the high Andes (Rademaker et al., 2014; Goldberg et al., 2016).
**Figure S5.** Spearman rank correlation matrix of variables from Fig. S4 using high (Khomer Khocha, Caserococha, and Compuerta), mid (Huamanmarca, Miski, Titicaca, Chorreras, Baja), and low groups (Refugio, Chochos, Llaviucu, Pacucha, Siberia) for *Polylepis* and charcoal. The Spearman rho coefficients are depicted in red (negative correlation) and blue (positive correlation). The merged charcoal (all sites) was significantly correlated (p<0.05) with the charcoal signal divided in low mid and high elevation groups that were also consistent with all other proxies. This suggests that the same trend was observed regardless of the grouping. The PLV (merged) and the high and low groups were significantly correlated (p<0.05) and consistent with all other proxies. However the mid elevation group was not in phase with the low or high elevation group or the merged PLV (i.e. negatively correlated). Given that all but one correlation was consistent (mid elevation set), charcoal and *Polylepis* pollen data were merged. Note that this analysis (correlation matrix using 3 groups) should be taken as preliminary because it leads to periods with insufficient number of sites per group (sites, n<3) to actually estimate any central tendency parameter. Note that additional sites would be required to evaluate whether a 3-group elevational distribution of *Polylepis* persists particularly because most of the sites in the mid elevation group were glaciated during the late Pleistocene (sections marked with asterisks in Fig. 2) and did not registered pollen or charcoal that was recorded in ice-free sites at higher or lower elevations. For instance, true absence for *Polylepis* or charcoal cannot be assumed for sites like Miski (13º 02’S, 3830 m) or Huamanmarca (13º 03’S, 3900 m) that were glaciated during the Pleistocene because Pacucha (13º 60’S, 3090 m), Refugio (13º 09’S, 3389 m) and Caserococha
(13° 32’S, 3980 m) that remained ice free registered *Polylepis* above and below Miski and Huamanmarca in the same region (similar latitude, Fig. 1). Additional sites (not currently available) would be required to further evaluate the possibility of specific migration patterns at species level.

**References**


