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Putting the rise of the Inca Empire within a climatic and land management context

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Abstract

The rapid expansion of the Inca from the Cuzco area of highland Peru produced the largest empire in the New World between ca. AD 1400–1532. Although this meteoric rise may in part be due to the adoption of innovative societal strategies, supported by a large labour force and standing army, we argue that this would not have been possible without increased crop productivity, which was linked to more favourable climatic conditions. A multi-proxy, high-resolution 1200-year lake sediment record was analysed at Marcacocha, 12 km north of Ollantaytambo, in the heartland of the Inca Empire. This record reveals a period of sustained aridity that began from AD 880, followed by increased warming from AD 1100 that lasted beyond the arrival of the Spanish in AD 1532. These increasingly warmer conditions allowed the Inca and their predecessors the opportunity to exploit higher altitudes from AD 1150, by constructing agricultural terraces that employed glacial-fed irrigation, in combination with deliberate agroforestry techniques. There may be some important lessons to be learnt today from these strategies for sustainable rural development in the Andes in the light of future climate uncertainty.

1 Introduction

Through the use of regional-scale, multidisciplinary studies it is becoming increasingly evident that many prehistoric South American cultures were highly adaptable and able to ensure food security even under sustained periods of harsh climatic conditions. For example, coastal societies such as the Moche and the Nasca flourished in arid regions by developing sophisticated irrigation technologies to cope with extremes of water availability (Schreiber and Lancho Rojas, 1995; Bawden, 1996). Highland cultures, on the other hand, not only had to deal with seasonal water supplies, but also had to combat large temperature ranges and steep terrain. A variety of innovative coping-strategies were therefore developed that included raised field systems (e.g. Tiwanaku; Erickson

1999, 2000) and the use of major terracing and irrigation systems to maximise land-use and reduce soil erosion (e.g. Wari; Williams, 2006).

The Inca of the south-central Andes were particularly successful in developing sustainable landscape practices. After a prolonged period of cultural development (ca. AD 1100–1400) they rapidly expanded beyond their heartland region of the Cuzco Valley (Bauer, 2004). By the time of European contact in 1532 the Inca had become the largest empire to develop in the Americas, controlling a region stretching from what is today northern Ecuador to central Chile and supporting a population of more than 8 million. While the factors involved in their sudden collapse under the stress of the Spanish invasion, the introduction of new diseases and civil wars have been well documented (Hemming, 1970), relatively little scholarly attention has been focused on their rapid rise as a pan-Andean power. While part of the reason behind this expansion has been attributed to the development of new economic institutions and revolutionary strategies of political integration (e.g. Covey, 2006), these social advances had to be underpinned by the ability to generate agricultural surplus that could sustain large populations, including the standing armies necessary for wide-ranging military campaigns.

Mountain environments provide particular challenges for any sizeable, agriculturally-dependent culture, requiring competent management of production levels, the development of sustainable landscape practices and the ability to facilitate altitudinal and/or latitudinal migration of animals, crops and people in response to climatic variations, often on a large scale. Documenting in detail the environmental backdrop against which the Inca accomplished their expansion enhances our understanding of the social, political and economic challenges that they faced. One of the difficulties in achieving this, however, is that the substantive part of the rise of the Inca took place over several centuries; a longer-term environmental perspective is therefore needed to understand the social and ecological contexts in which this development took place. Accordingly, in this study we provide a detailed synthesis of a 1200-year palaeoenvironmental dataset derived from a climatically-sensitive sedimentary sequence located in the Inca heartland. New proxy data, chosen for their ability to reflect both palaeoclimatic and anthropogenic

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change, are combined with existing floral, faunal and sedimentological records from the sequence in order to establish a palaeoenvironmental framework against which human responses can be assessed.

2 Site selection

The agriculturally-rich region of Cuzco has a long and complex occupational history (Bauer, 2004). Long before the Inca state developed, parts of the Cuzco region were occupied by the Ayacucho-based Wari state (AD 550–1000). It is widely suggested that their decline was accelerated by worsening environmental conditions that decreased opportunities for agrarian intensification in the south-central Andes at that time (Williams, 2001, 2002, 2006). The decline of the Wari ushered in a period of regional development with the initiation of the Inca state that later culminated in a relatively brief yet significant period of imperial expansionism. While the basic contours of this historic development have received increased attention over the past several decades, the palaeoenvironmental landscape on which these events took place remains largely unexplored.

One site in the Cuzco region that has already provided a continuous, highly detailed multi-proxy palaeoenvironmental record is that of Marcacocha (Chepstow-Lusty et al., 1996, 1998, 2003). Located within the Patacancha Valley, some 12 km north of the major Inca settlement of Ollantaytambo, Marcacocha (13°13′ S, 72°12′ W, 3355 m above sea-level [a.s.l.]) is a small (ca. 40 m diameter) circular, in-filled lake set within a larger basin (Fig. 1). The surrounding slopes constitute an ancient, anthropogenically-modified landscape, being extensively covered with Inca and pre-Inca agricultural terraces (Fig. 2). The in-filled lake site is separated from the Patacancha River by the promontory of Huchuy Aya Orqo, which contains stratified archaeological deposits that range from the Early Horizon period (ca. 800 BC) to Inca times (Kendall and Chepstow-Lusty, 2006). Today, the flat area adjacent to the in-filled lake provides space for minor potato cultivation and is used for grazing cattle, sheep, goats and horses. In the past, the site was also important for pasturing camelids, owing to its location along a former trans-Andean caravan route that linked the Amazonian selva in the east to the main western highland trading centres. Because the Patacancha River is fed partially by melt-water, it flows throughout the year, which may explain why the basin always remains wet despite a markedly seasonal climate. The constancy of the river is also likely to have been a significant factor in ensuring long-term occupation around the site and probably accounts for the exceptional preservation of the organic deposits in the former lake.

In 1993, an 8.25 m stratigraphically-continuous sediment core that spanned the last 4000 years was recovered from the centre of the basin for high-resolution palaeoecological analysis (Chepstow-Lusty et al., 1996, 1998, 2003). The chronology for the sequence was derived from six radiocarbon dates and seven ^{210}Pb dates (Table 1). Confirmation of the sensitivity of the site to palaeoclimatic change comes from sub-centennial pollen analysis of the sequence, which documents the lake-level response to regional precipitation changes and records a series of aridity episodes broadly corresponding with regional cultural transitions indicated by an independently-derived archaeological chronology (Fig. 3) (Chepstow-Lusty et al., 2003; Bauer, 2004). Other previous work carried out on the sequence includes an assessment of basic sedimentological characteristics (including carbonate, organic and non-organic content) and, from the top 1.9 m, an analysis of oribatid mite remains, thought to be an indirect indicator of large domestic herbivore densities in the catchment over the past ca. 1200 years (Chepstow-Lusty et al., 2007).

In order to help understand potential links between past environmental and cultural change in the region, the existing palaeoenvironmental datasets from Marcacocha were assessed alongside new, complementary proxy analyses. Carbon/nitrogen (C/N) and δ^{13}C data obtained from organic matter can provide insights into the amount and type of organic material entering a lake system. If supported by additional plant macrofossil evidence, this information can help to document catchment vegetation changes through time (Meyers and Teranes, 2001). Variations in macrocharcoal levels, on the other hand, can be used in reconstructing fire frequency histories and are often indicative of anthropogenic activity in the landscape (e.g. Whitlock and Larsen, 2001). Samples for all analyses were taken every centimetre, providing a ca. 6-year temporal resolution spanning the last 1200 years (assuming constant sedimentation rates).

3 Methods

3.1 Macrofossils

Three sets of 1 cm^3 volumetric sub-samples were taken every centimetre throughout the top 1.9 m of the sequence. One set of these sub-samples was oxidized with 30% hydrogen peroxide in test tubes placed in a hot water bath at 60°C for 2–4 h. The residue was then sieved and charcoal particles >125 µm counted using a low-power dissecting microscope. Sub-samples from the second set were disaggregated in deionised water and macrofossils including seeds, charophyte oospores and faunal remains were then hand-picked under a low-power dissecting microscope.

3.2 Organic matter geochemistry

$^{13}C/^{12}C$ ratios were measured by combustion of the third set of sub-samples in a Carlo Erba 1500 elemental analyser on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer, with $\delta^{13}C$ values calculated to the VPDB scale using a within-run laboratory standard (BROC1) calibrated against NBS-19 and NBS-22. Replicate analysis of well-mixed samples indicated a precision of $+<0.1‰$ (1σ). Total organic carbon (%TOC) and total nitrogen (%TN) were also measured simultaneously; these results were calibrated against an Acetanilide standard. C/N is calculated from %TOC and %TN. Replicate analysis of well-mixed samples indicated a precision of $+<0.1\%$.

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3.3 Charcoal analysis

The raw charcoal accumulation rate data (C) were first interpolated to 7-year time-steps, a value that corresponds approximately to the median temporal resolution of the entire charcoal record (Higuera et al., 2007, 2008). The resulting interpolated data (C_i) were then separated into background (C_b), and peak (C_p) components. Low-frequency background variations in a charcoal record (C_b) represent changes in charcoal production, sedimentation, mixing and sampling, and are removed to obtain a residual series of "peak" events (C_p), i.e. $C_p = C_i - C_b$. It is assumed that C_p itself comprises two sub-components: C_{noise}, representing variability in sediment mixing, sampling and analytical and naturally occurring noise; and C_{fire}, representing charcoal input from local fire events (likely to be related to the occurrence of one or more local fires occurring within ca. 1 km of the site; Higuera et al., 2007). For each sample, a Gaussian mixture model was used to identify the C_{noise} distribution, the 99th percentile of which was then used to define a threshold separating samples into "fire" and "non-fire" events (Higuera et al., 2008). The C_b component was estimated by means of a locally-weighted regression using a 500-year window; in all cases, the window width used was that which maximized the signal-to-noise index and the goodness-of-fit between the empirical and modelled C_p distributions. All numerical treatments were carried out using the CharAnalysis program (© Philip Higuera). Fire history was described by quantifying the variation of fire return intervals (FRI, years between two consecutive fire events) over time, and smoothed using a locally-weighted regression with a 1000-year window.

4 Results

New proxy data are plotted alongside selected pollen taxa in Fig. 4; the application of binary splitting techniques to all data (Birks and Gordon, 1985) suggests five main zones.

4.1 Prior to AD 880

At the very base of the sequence, this interval is notable only for its low pollen concentrations and the lowest %TOC and %TN than in any subsequent zone. Analysis of the moderate-low concentrations of macrocharcoal suggest three significant fire events over this interval (Fig. 5c).

4.2 AD 880–1100

At ca. AD 880 an increase in Cyperaceae and Chenopodiaceae pollen concentrations is notable, followed by a marked decline through the rest of the interval. In contrast, pollen concentrations of the shallow water plant taxon *Myriophyllum* undergo expansion only in the later part of the interval. Decreases in δ^{13}C mirror the chenopod and sedge records; macrocharcoal levels remain suppressed throughout.

4.3 AD 1100–1400

A critical threshold for biological activity appears to have been crossed at the beginning of this period, when high concentrations of *Alnus* pollen are noted for the first time. In addition, Juncaceae seeds become prominent, reflecting the importance of this family as a major component of the lakeside vegetation. Synchronously, charophyte oospores and macrocharcoal concentrations also increase notably, the latter providing evidence for three significant fire events during this interval (Fig. 5c).

4.4 AD 1400–1540

This interval is notable for the continued rise in *Alnus* pollen concentrations to the highest values in the sequence (peaking ca. AD 1450). This period also contains a significant decline in δ^{13}C, matched by a progressive decrease in C/N (both of which only recover at the very end of the interval). Oribatid mite concentrations undergo a marked rise in the second half of the interval, only then to decline suddenly.

4.5 Post AD 1540

Concentrations of *Alnus* pollen decline throughout this zone, as does $\delta^{13}C$. Conversely, concentrations of Cyperaceae pollen increase, whereas C/N, Juncaceae seeds and macrocharcoal concentrations remain relatively steady throughout, though all witness peak values ca. AD 1800. Interestingly, concentrations of charophytes and oribatid mite remains appear to co-vary inversely, the principal mite peak (and minimum charophyte values) occurring ca. AD 1750. This interval is also characterised by the highest fire frequency of the entire record, with eight major fire events being identified (Fig. 5).

5 Interpretation and discussion

5.1 Prior to AD 880

During much of the first millennium AD, the pollen record indicates little evidence for sustained agriculture at Marcacocha (see also Fig. 3). Indeed, Chenopodiaceae pollen, which probably includes a number of cultivars such as *Chenopodium quinoa*, is rare (Chepstow-Lusty et al., 2003), suggesting suppressed, cool temperatures over this period. Furthermore, the sediments in this interval are characterised by a lower %TOC than subsequent periods, suggesting greater erosion in the immediate catchment, bringing in more inorganic material. Independent evidence from ice core, archaeological, archaeobotanical and geomorphological data indicate that much of this period was characterized by relatively low temperatures, a factor that would have encouraged concentration of human populations at lower altitudes (Thompson et al., 1995; Kendall and Chepstow-Lusty, 2006; Johannessen and Hastorf, 1990; Seltzer and Hastorf, 1990). Nevertheless, a period of burning close to the upper limit of this interval suggests that there may latterly have been a limited agricultural activity in the basin.

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5.2 AD 880–1100

An increase in Cyperaceae pollen concentrations at the beginning of this period probably reflects sedge colonization at the lake margin as the lake-level reduced in response to increasingly arid conditions (Chepstow-Lusty et al., 2003). This interpretation is supported by a major peak in C/N and a corresponding minimum in δ^{13}C, all of which suggest abundant terrestrial plant material (high C/N, low δ^{13}C) entering the lake from the catchment. Furthermore, the marked appearance of the shallow-water taxon *Myriophyllum* at ca. AD 1000 also suggests low lake-levels and increasing levels of nutrients. A short-lived peak in Chenopodiaceae pollen concentrations (associated with the presence of maize pollen) at the beginning of this interval indicates that increasing temperatures allowed limited agriculture. Nevertheless, despite the rare subsequent appearance of maize pollen (Fig. 3), macrocharcoal levels remain suppressed for almost the next 250 years, implying that the basin was used for mostly pastoral purposes. This interpretation is reinforced by the mite record, which shows a sustained increase in frequencies that peak at the end of this interval, suggesting that the basin was increasingly used by indigenous societies keen to exploit an area of natural, well-watered pasture in the face of increasing climatic aridity.

5.3 AD 1100–1400

The marked increase in *Alnus* pollen at the beginning of this interval reflects the rapid expansion into the immediate catchment (probably from lower altitudes) of *Alnus acuminata*, a species closely associated with the colonization of degraded soils and, subsequently, with agroforestry (Chepstow-Lusty and Winfield, 2000). This is the first sustained appearance of *Alnus* in the entire 4200-year record, suggesting that the occasional pollen grains recorded prior to this are likely to represent long-distance transport. The increase in Juncaceae seeds indicate that lake-levels continued to drop and the increases in both charophyte oospores and δ^{13}C suggest that these shallowing lacustrine conditions supported increasing levels of charophyte algae (even though

C/N remains high). Combined, these data all point to a significant rise in temperature, though without any concurrent increase in precipitation (the hydrological requirements of *A. acuminata* probably being met year-round by the adjacent, glacially-fed Patacancha River).

It is likely that a sustained warmer climate enabled human populations to return to traditional agricultural use of the Marcacocha Basin and the surrounding landscape. Evidence of this is provided by the presence of chenopod and (rare) maize pollen. In addition, heightened macrocharcoal values centring on ca. AD 1170 are likely to reflect a period of increased burning and agricultural clearance. The brief yet marked reduction in %TOC at this time suggests erosion linked to a period of landscape transformation (possibly including terrace building), effectively stabilizing the catchment soils for the next 650 years (Donkin, 1979). The sustained increase in C/N ratios for almost 50 years immediately after this event supports the notion of more soil-derived organic matter and/or the increased influence of terrestrial vegetation. This postulated change around the basin back to more agricultural land-use probably pushed pastoralism to higher altitudes, as suggested by the decline in mite concentrations.

A further noticeable period of burning centred on ca. AD 1300 corresponds with a decline of charophyte oospores, when nutrients may have entered the lake (charophytes favour shallow, relatively nutrient-poor conditions). This may represent a shift in land-use but, unlike the initial burning at the beginning of the interval, it was not associated with erosion into the lake, suggesting that the landscape was already stabilised by terraces by this time.

5.4 AD 1400–1540

This interval, which coincides with a period of rapid Inca expansion outside of the Cuzco heartland, appears to have been relatively stable from a climatic point of view. Temperatures seemed to have remained warm, with precipitation (and corresponding lake-levels) being low. Despite this climatic stability, significant land-use changes occurred in the basin. The increasing commercial importance of the Patacancha Valley caravan route is reflected in the sharp rise in mite abundances from the mid-1400s, suggesting an increased density of large herbivores (particularly llamas) in the catchment (Chepstow-Lusty et al., 2007). This interpretation is supported by a decline in C/N and $\delta^{13}C$, suggesting a terrestrial vegetation component that may in part derive from increased agriculture (including maize cultivation). In addition, terrestrial plant material was probably being incorporated in animal excreta originating from the lake margin (higher %TN also supports this hypothesis). The influx of nutrients to the lake appears to have suppressed charophyte levels, which decline almost to zero by the end of the period. Furthermore, there is only muted evidence for sustained burning of the landscape over this period.

5.5 Post AD 1540

C/N decreases following the collapse of the Inca Empire (AD 1532); suggesting a greater organic matter contribution from aquatic plants (possibly fringing macrophytes), linked to reduced management of vegetation such as Juncaceae growing around the lake. The marked recovery in charophyte oospore concentrations suggests a continuation of low lake-levels and a major decline in pasture usage. This latter inference is supported by the crash in mite abundances and their subsequent slow recovery, probably reflecting the decline in llama caravans on the adjacent Inca commercial route and forced migration of rural populations under Spanish rule (Chepstow-Lusty et al., 2007). Mite abundances undergo one final increase from around ca. AD 1600, when the Spanish began introducing new large domesticated herbivores from the Old World, such as sheep, cattle, goats and horses. This increased use of the basin for pasturing animals is supported by macrocharcoal concentrations, which show sustained and significant burning events (presumably for clearance purposes) just prior to, and throughout, the 17th century. A hiatus in burning activity during much of the following century coincides with the collapse and subsequent recovery of mite populations; a resumption of landscape burning accompanies the final decline in mite populations throughout the 19th and 20th centuries. It is interesting to note that several independent regional reconstructions of biomass burning activity in South America show a decreasing fire frequency for the past 500 years and attribute this pattern to a range of climatic controls (e.g. Bush et al., 2008; Marlon et al., 2008; Nevle and Bird, 2008). The record at Marcacocha, however, shows the opposite trend (i.e. that fire frequency increases over this period; Fig. 5d), suggesting that it is local human activity influencing the fire history of the basin, and not climatic factors.

6 A broader context

The pattern of change witnessed at Marcacocha in the centuries that pre-dated the imperial expansion of the Inca can be summarized as: (1) a period of relative aridity developing from ca. AD 880, characterised by low lake-levels and a limited arable-based economy in the valley that gave way to more pastoralism at the beginning of the second millennium AD; and (2) an interval of elevated temperatures from ca. AD 1100 that probably lasted for four centuries or more (the upper limit is difficult to define). This latter, warmer period is of particular interest, since it witnessed significant human presence in the basin in terms of agriculture, early landscape modification and later trading activity. In order to properly understand the broader-scale cultural and climatic conditions over this interval, it is necessary to assess the extent to which events happening in one Andean valley may have reflected what was happening regionally. In part, this can be achieved by comparison of the Marcacocha record with other, independently-derived datasets.

The Quelccaya ice cap, located some 200 km to the southeast of Marcacocha at 5670 m a.s.l. in southern Peru, arguably provides the best-resolved climatic archive from the region (Thompson et al., 1984, 1986, 1988). Two overlapping cores drilled though the ice to bedrock provide a composite, annually-resolved record of the last 1500 years. While the use of proxies from this record as a yardstick for central Andean climatic variability is not without controversy (in particular, the complex relationships between δ^{18}O variability and temperature, and ice accumulation and regional

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precipitation; Thompson et al., 1988; Grootes et al., 1989; Ortlieb and Macharé 1993; Gartner, 1996; Thompson et al., 2000; Calaway 2005), one unambiguous dataset from the Quelccaya record is that of dust content. At present, dust layers form annually on the surface of the glacier during the dry season, when dominantly southerly to northwesterly winds pick up material from the bare, recently-harvested agricultural areas of the Altiplano (Thompson et al., 1984, 1988). It has been postulated that the two most prominent dust events from the 1500-year Quelccaya record (centring on AD 600 and AD 920) may have their origin in anthropogenic activity, since they do not correspond with any marked climatic shifts.

The latter of these two prominent dust events lasts around 130 years and is characterized by a steady accumulation from AD 830 to a peak at AD 920, followed by a more rapid decline to about AD 960. It has been suggested that this pattern may be linked with intensified raised field agriculture around Lake Titicaca (Thompson et al., 1988) and/or may be representative of a wider spectrum of human activity in the region, including terrace construction (Erickson, 2000). At Marcacocha, this interval is represented by high concentrations of Cyperaceae pollen, supported by high C/N and low δ^{13}C values, suggesting reduced lake-levels and a significant proportion of terrestrial plant matter entering the lake. Although no significant agricultural palynological indicators were found in the Quelccaya record to support the notion of anthropological activity within the landscape over this interval (Thompson et al., 1988), both chenopod (probably incorporating quinoa) and maize pollen are notable at Marcacocha, strongly suggesting agricultural use of the basin at this time.

It is also worth noting that some authorities have used the Quelccaya ice core data, as well as sediment records from Lake Titicaca that are indicative of low lake-levels, to infer a serious drought at ca. AD 1000–1100 (e.g. Thompson et al., 1988; Abbott et al., 1997; Binford et al., 1997). Furthermore, it is argued that this protracted period of aridity may (or may not) have been influential in hastening the demise of both the Tiwanaku and Wari cultures, centred on the southern shores of Titicaca and around Ayacucho, respectively (e.g. Binford et al., 1997; Erickson, 1999, 2000). Regardless of the merits of these arguments, the Marcacocha record nonetheless indicates that dry conditions began at least a century prior to ca. AD 1000 in the Cuzco region.

The rich archaeological record around Cuzco can also help in understanding the Marcacocha data over this crucial interval. It is from ca. AD 1200 (although perhaps as early as ca. AD 1000) that the Inca people in the Cuzco region are recognized archaeologically by the occurrence of Killke pottery (Rowe, 1944; Bauer, 2004). At Marcacocha, there is a marked increase in the frequency of archaeological finds dated to after ca. AD 1000, such as from the promontory of Juchuy Aya Orqo, adjacent to the lake (Kendall and Chepstow-Lusty, 2005). This is corroborated by the Marcacocha charcoal record, which also suggests a notable increase in anthropogenic activity in the valley from ca. AD 1150. These data all point to a dramatic expansion and/or migratory influx of populations from lower altitudes over this interval, possibly accompanied by growth in economic activities.

From an even broader perspective, the notion that temperatures were consistently higher than modern values during the 9th–14th centuries has received increasing attention in the Northern Hemisphere (Lamb, 1965; Hughes and Diaz, 1994). The prevailing view of this interval, known commonly as the "Medieval Warm Period" (MWP), is that elevated temperatures were often only intermittently experienced and, in some regions, was apparently characterized instead by climatic anomalies such as prolonged drought, increased rainfall or a stronger monsoon system (Hughes and Diaz, 1994; Bradley et al., 2003; Stine, 1994; Zhang et al., 2008). However, evidence for the MWP being a global phenomenon is contentious, especially in the Southern Hemisphere, where there are few continuous, detailed palaeoclimatic records spanning this interval (Bradley, 2000; Broecker, 2001). Nevertheless, from the Marcacocha dataset we can infer that temperatures increased from ca. AD 1100 (after a period of relative aridity in comparison to much of the first millennium AD) and that conditions remained warm and stable for several centuries thereafter.

7 Conclusions

This study provides evidence that environmental and cultural events may be linked in the Cuzco region. The scale of anthropological manipulation and transformation of the landscape in the south-central Andes appears to have increased after ca. AD 1100, probably in response to a climatic backdrop that was relatively warm, dry and essentially stable. The development of major irrigated terracing technology was increasingly necessary in these regions to obviate conditions of seasonal water stress, thereby allowing efficient agricultural production at higher altitudes. The outcome of these strategies was greater long-term food security and the ability to feed large populations. Such developments were exploited by the Inca of the Cuzco Valley, who were emerging as the dominant ethnic group of the region as early as ca. AD 1200. A healthy agricultural surplus supported their economic and political potential, enabling them to subjugate other local independent states and to effectively centralize power in the Cuzco region by ca. AD 1400 (Bauer, 2004).

Fully understanding the adaptive capacity-building strategies of the Inca in the face of demanding climatic conditions is still at an early stage. However, their success has clear implications for both rural and urban Andean communities facing the environmental challenges currently being posed by global warming.

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References

Abbott, M. B., Binford, M. W., Brenner, M., and Kelts, K. R.: A 3500 ^{14}C yr high resolution record of water-level changes in Lake Titicaca, Quat. Res., 47, 169–180, 1997.

Bauer, B.: Ancient Cuzco: Heartland of the Inca, University of Texas Press, Austin, 2004.

Bawden, G.: The Moche, Blackwell Publishers, Cambridge, 1996.

Binford, M. W., Kolata, A. L., Brenner, M. Janusek, J. W., Seddon, M. T., Abbott, M., and Curtis, J. H.: Climate variation and the rise and fall of an Andean civilization, Quat. Res., 47, 171–186, 1997.

Birks H. J. B. and Gordon A. D.: Numerical Methods in Quaternary Pollen Analysis, Academic Press, San Diego, 1985.

Bradley, R.: Paleoclimate – 1000 years of climatic change, Science, 288, 1353–1354, 2000.

Bradley, R. S., Hughes, M. K., and Diaz, H. F.: Climate in Medieval time, Science, 302, 404–405, 2003.

Broecker, W.: Was the Medieval Warm Period global?, Science, 291, 1497–1499, 2001.

Bush, M. B., Silman, M. R., McMichael, C., and Saatchi, S.: Fire, climate change and biodiversity in Amazonia: a Late-Holocene perspective, Philos. T. Roy. Soc. B., 363, 1795–1802, 2008.

Calaway, M. J.: Ice cores, sediments and civilization collapse: a cautionary tale from Lake Titicaca, Antiquity, 79, 778–790, 2005.

Chepstow-Lusty, A. and Winfield, M.: Agroforestry by the Inca: Lessons from the past, Ambio, 29, 322–328, 2000.

Chepstow-Lusty, A., Bennett, K. D., Fjeldså, J., Kendall, A., Galiano, W., and Tupayachi Herrera, A.: Tracing 4000 years of environmental history in the Cuzco area, Peru, from the pollen record, Mt. Res. Dev., 18, 159–172, 1998.

Chepstow-Lusty, A., Bennett, K. D., Switsur, V. R., and Kendall, A.: 4000 years of human impact and vegetation change in the central Peruvian Andes – with events paralleling the Maya record? Antiquity, 70, 823–833, 1996.
Chepstow-Lusty, A., Frogley, M. R., Bauer, B. S., Bush, M. B., and Tupayachi Herrera, A.: A late Holocene record of arid events from the Cuzco region, Peru, J. Quat. Sci., 18, 491–502, 2003.
Chepstow-Lusty, A., Frogley, M. R., Bauer, B. S., Leng, M., Cundy, A., Boessenkool, K. P., and Gioda, A.: Evaluating socio-economic change in the Andes using oribatid mite abundances as indicators of domestic animal densities, J. Archaeol. Sci., 34, 1178–1186. 2007.
Covey, R. A.: How the Incas Built Their Heartland: State Formation and the Innovation of Imperial Strategies in the Sacred Valley, Peru, University of Michigan Press, Ann. Arbor, 2006.
Donkin R.: Agricultural Terracing in the Aboriginal New World, Viking Fund Publications in Anthropology 56, Wenner-Gren Foundation for Anthropological Research, New York, 1979.
Erickson, C.: Neo-environmental determinism and agrarian "collapse" in Andean prehistory, Antiquity, 73, 634–642, 1999.
Erickson, C.: The Lake Titicaca Basin: A Precolumbian built landscape, in: Imperfect Balance: Landscape Transformations in the Precolumbian Americas, edited by: Lentz, D. L., Columbia University Press, New York, 2000.
Flynn, W. W.: Determination of low levels of polonium-210 in environmental materials, Anal. Chim. Acta, 43, 221–226, 1968.
Gartner W. G.: Book review of "The Tiwanaku: Portrait of an Andean Civilization" by A. L. Kolata, Ann. Ass. Am. Geog., 86, 153–156, 1996.
Grootes, P. M., Stuiver, M., Thompson, L. G., and Mosley-Thompson, E.: Oxygen isotope changes in tropical ice, Quelccaya, Peru, J. Geophys. Res., 91, 1187–1194, 1989.
Hemming, J.: The Conquest of the Incas, Harcourt Brace Jovanovich, New York, 1970.
Hughes, M. K. and Diaz, H. F.: Was there a Medieval Warm Period, and if so, where and when? Climatic Change, 26, 109–142, 1994.
Higuera, P. E., Brubaker, L. B., Anderson, P. M., Brown, T. A., Kennedy, A. T., and Hu, F. S.: Frequent fire in ancient shrub tundra: implications of paleorecords for Arctic environmental change, PLoS ONE, 3, e0001744, doi:10.1371/journal.pone.0001744, 2008.
Higuera, P. E., Peters, M. E., Brubaker, L. B., and Gavin, D. G.: Understanding the origin and analysis of sediment-charcoal records with a simulation model, Quat. Sci. Rev., 26, 1790–

1809, 2007.
Johannessen, S. and Hastorf, C.: A history of fuel management (AD 500 to the present) in the Mantaro Valley, Peru, J. Ethnobiology, 10, 61–90, 1990.
Kendall, A. and Chepstow-Lusty, A.: Cultural and environmental change in the Cuzco region of Peru: the rural development implications of combined archaeological and palaeoecological evidence, in: Kay Pacha: Cultivating Earth and Water in the Andes, edited by: Dransart, P., British Archaeological Reports International Series, Archaeopress, Oxford, 1478, 185–197, 2006.
Lamb, H. H.: The early medieval warm epoch and its sequel, Palaeogeogr. Palaeocl., 1, 13–37, 1965.
Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., and Prentice, I. C.: Climate and human influences on global biomass burning over the past two millennia, Nat. Geosci., 1, 697–702, 2008.
McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. G., and Reimer, P. J.: SHCal04 southern hemisphere calibration 0–1000 cal BP, Radiocarbon, 46, 1087–1092, 2004.
Meyers, P. A. and Teranes, J. L.: Sediment organic matter, in: Tracking Environmental Change Using Lake Sediments: Volume 2, edited by: Last, W. M. and Smol, J. P., Kluwer Academic Publishers, Dordrecht, 239–269, 2001.
Nevle, R. J. and Bird, D. K.: Effects of syn-pandemic fire reduction and reforestation in the tropical Americas on atmospheric CO_2 during the European conquest, Palaeogeogr. Palaeocl., 264, 25–38, 2008.
Ortlieb, L. and Macharé, J.: Former El Niño events: records from western South America, Global Planet. Change, 7, 181–202, 1993.
Ortloff, C. R. and Kolata, A. L.: Climate and collapse: agro-ecological perspectives on the decline of the Tiwanaku State, J. Archaeol. Sci., 20, 195–221, 1993.
Rowe, J. H.: An introduction to the archaeology of Cuzco, Papers of the Peabody Museum of American Archaeology and Ethnology, 27, Harvard University Press, Cambridge, 1944.
Schreiber, K. J. and Lancho Rojas, J.: The Puquios of Nasca, Lat. Am. Antiq., 6, 229–254, 1995.
Seltzer, G. and Hastorf, C.: Climatic change and its effect on Prehispanic agriculture in the central Peruvian Andes, J. Field Archaeol., 17, 397–414, 1990.
Stine, S.: Extreme and persistent drought in California and Patagonia during Medieval time,

Nature, 269, 546–549, 1994.
Stuiver, M. and Reimer, P. J.: Extended ^{14}C database and revised CALIB 3.0 ^{14}C age calibration program, Radiocarbon, 35, 215–230, 1993.
Thompson, L. G., Davis, M. E., Mosley-Thompson, E., and Liu, K.-B.: Pre-Incan agricultural activity recorded in dust layers in two tropical ice cores, Nature, 307, 763–765, 1988.
Thompson, L. G., Mosley-Thompson, E., and Arnao, B. M.: El Niño-Southern Oscillation events recorded in the stratigraphy of the tropical Quelccaya ice cap, Peru, Science, 226, 50–53, 1984.
Thompson, L. G., Mosley-Thompson, E., Dansgaard, W., and Grootes, P. M.: The Little Ice Age as recorded in the stratigraphy of the tropical Quelccaya ice cap, Science, 234, 361–364, 1986.
Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P.-N., Henderson, K. A., Cole-Dai, J., Bolzan, J. F., and Liu, K.-B.: Late glacial stage and Holocene tropical ice core records from Huascaran, Peru, Science, 269, 46–50, 1995.
Thompson, L. G., Mosley-Thompson, E., and Henderson, K. A.: Ice-core palaeoclimate records in tropical South America since the Last Glacial maximum, J. Quat. Sci., 15, 377–394, 2000.
Williams, P. R.: Cerro Baúl: A Wari center on the Tiwanaku frontier, Lat. Am. Antiq., 12, 67–83, 2001.
Williams, P. R.: Rethinking disaster-induced collapse in the demise of the Andean highland states: Wari and Tiwanaku, World Archaeol., 33, 361–374, 2002.
Williams, P. R.: Agricultural innovation, intensification and sociopolitical development: the case of highland irrigation agriculture on the Pacific Andean watersheds, in: Agricultural Strategies, edited by: Marcus, J. and Stanish, C., Cotsen Institute of Archaeology, UCLA, Los Angeles, USA, 309–333, 2006.
Whitlock, C. and Larsen, C. P. S.: Charcoal as a fire proxy, in: Tracking Environmental Change Using Lake Sediments, Volume 3, edited by: Smol, J. P., Birks, H. J. B., and Last W. M., Kluwer Academic Publishers, Dordrecht, 75–97, 2001.
Zhang, P., Cheng, H., Edwards, R. L., Chen, F., Wang, Y., Yang, X., Liu, J., Tan, M., Wang, X., Liu, J., An, C., Dai, Z., Zhou, J., Zhang, D., Jia, L., and Johnson, K. R.: A test of climate, sun and culture relationships from an 1810-year Chinese cave record, Science, 322, 940–942, 2008.

Table 1. Bulk radiocarbon and ^{210}Pb dates for Marcacocha (adapted from Chepstow-Lusty et al., 2007). Radiocarbon dates were calibrated using the SHCal04 dataset (Stuiver and Reimer, 1994) in conjunction with the CALIB 5.0 calibration program (McCormac et al., 2004) and are cited as years before present (AD 1950). ^{210}Pb determinations followed Flynn et al. (1968).

Depth (cm)	Method	Laboratory Reference	^{14}C age (yr BP)	Calibrated age (cal. yr BP)	Calendar age
0–2	^{210}Pb				AD 1991
10–12	^{210}Pb				AD 1958
18–20	^{210}Pb				AD 1926
27–29	^{210}Pb				AD 1918
39–41	^{210}Pb				AD 1907
47–49	^{210}Pb				AD 1905
50–51	^{210}Pb				AD 1845
101–102	^{14}C	Beta-190482	400±40	410±80	AD 1540
115–123	^{14}C	Q-2917	620±50	590±50	AD 1360
210–218	^{14}C	Q-2918	1460±50	1320±60	AD 630
310–318	^{14}C	Q-2919	1805±50	1670±120	AD 280
478–486	^{14}C	Q-2920	2245±50	2190±150	BC 240
610–618	^{14}C	Q-2921	3650±60	3910±200	BC 1960

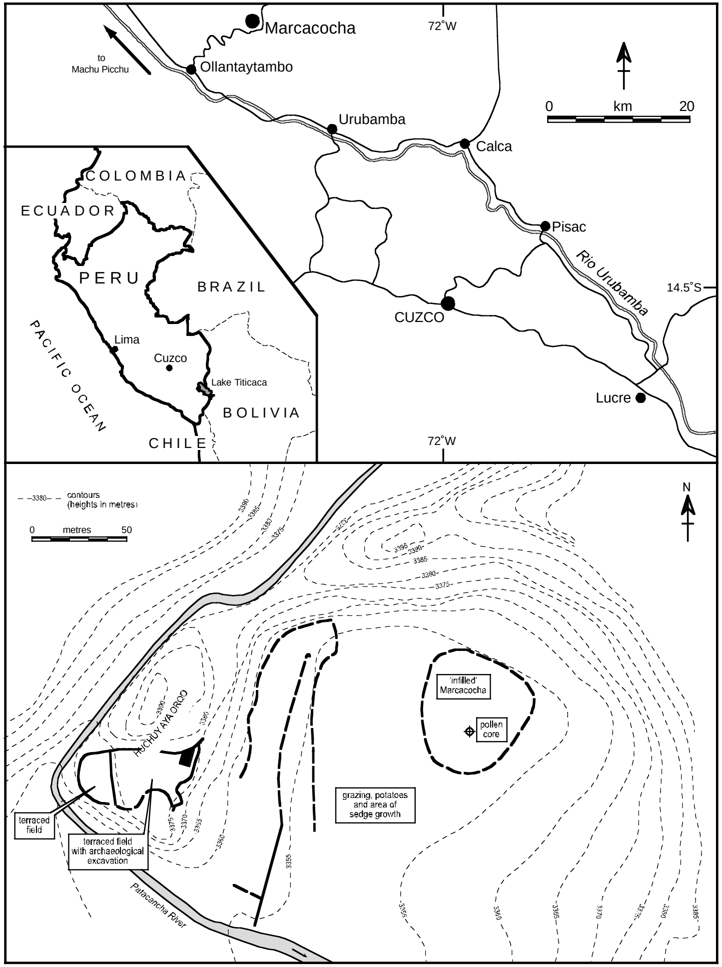

Fig. 1. Location maps.

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Fig. 2. General view north-eastwards up the Patacancha Valley over the in-filled lake of Marcacocha.

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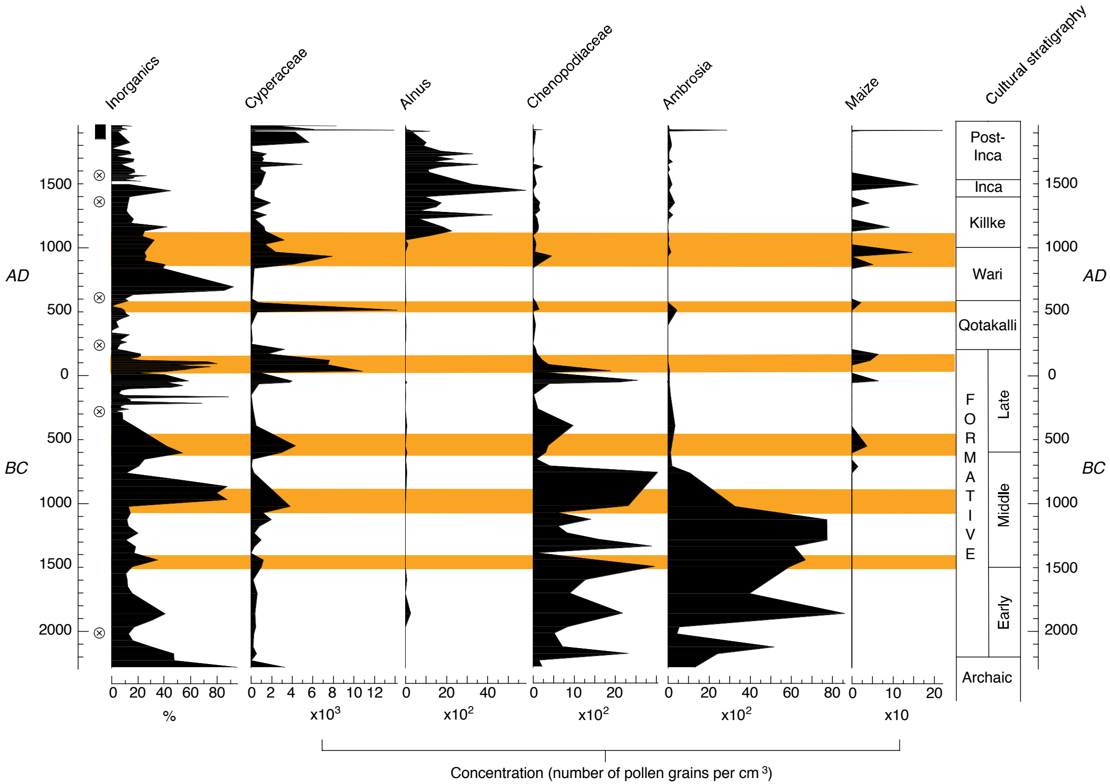

Fig. 3. Inorganic content (percentage) and pollen concentration diagram of selected taxa at Marcacocha plotted against age (adapted from Chepstow-Lusty et al., 2003). Shaded circles indicate calibrated radiocarbon dates; filled rectangle indicates range of ^{210}Pb dates (see Table 1). The independently-derived archaeological chronology for the Cuzco region is also indicated (Bauer, 2004). Shaded horizontal bands denote periods of aridity as inferred from the Cyperaceae record.

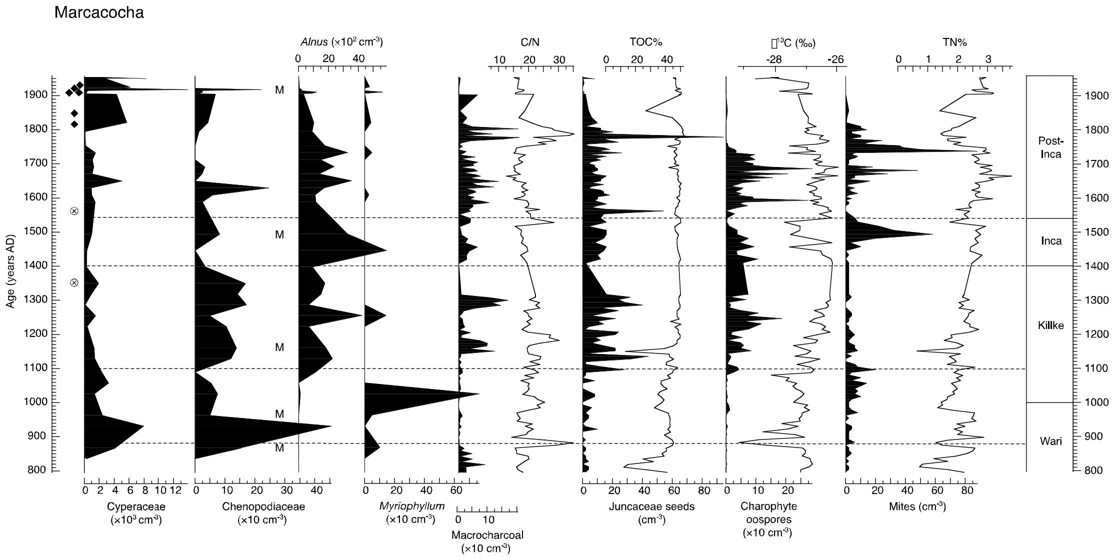

Fig. 4. Selected proxies and pollen taxa plotted against depth. Shaded circles indicate calibrated radiocarbon dates; filled diamonds indicate ^{210}Pb dates (see Table 1). "M" denotes occurrence of maize pollen; horizontal dashed lines delineate zones discussed in text. Absence of data in certain proxies between ca. 1320 and 1400 reflects where material sampled for radiocarbon dating is missing (represents an interval between 115 and 123 cm depth).

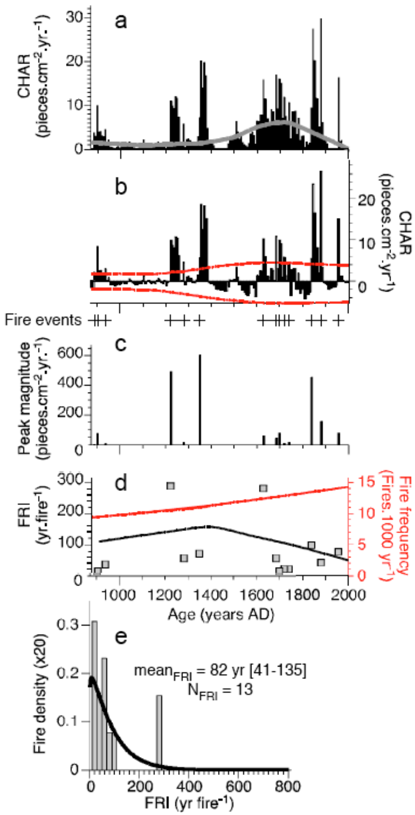

Fig. 5. Fire event reconstruction based on the raw charcoal accumulation rate (CHAR); see text for details. **(a)** represents the raw CHAR data interpolated to constant 7-year time intervals (C_i) (black columns), with the background signal (C_b) also shown (grey line); **(b)** de-trended CHAR data; **(c)** residual peaks and magnitude of detected fire events (+); **(d)** fire return interval (black line), inferred from time since last fire (grey squares), and simulated fire frequency (red line); **(e)** distribution of fire density.