Adaptive capacity of farming communities to climate change in the Peruvian Andes: past, present and future (preliminary findings of the ACCESS project)

Article

Published Version

Branch, Nicholas, Ferreira, Francisco, Lane, Kevin, Wade, Andrew ORCID logoORCID: https://orcid.org/0000-0002-5296-8350, Walsh, Douglas, Handley, Josephine, Herrera, Alex, Rodda, Harvey, Simmonds, Mike ORCID logoORCID: https://orcid.org/0000-0001-7845-0392, Meddens, Frank and Black, Stuart ORCID logoORCID: https://orcid.org/0000-0003-1396-4821 (2023) Adaptive capacity of farming communities to climate change in the Peruvian Andes: past, present and future (preliminary findings of the ACCESS project). Revista de Glaciares y Ecosistemas de Montaña, 8. pp. 51-67. Available at https://centaur.reading.ac.uk/113661/

Adaptive Capacity of Farming Communities to Climate Change in the Peruvian Andes: Past, Present and Future (Preliminary Findings of the ACCESS Project)

La Capacidad de Adaptación al Cambio Climático de las Comunidades Agrícolas en los Andes Peruanos: Pasado, Presente y Futuro (Conclusiones Preliminares del Proyecto ACCESS)

Nicholas Branch[1], Francisco Ferreira[1], Kevin Lane[2], Andrew Wade[1], Douglas Walsh[3], Josie Handley[4], Alex Herrera[5], Harvey Rodda[6], Mike Simmonds[7], Frank Meddens[4], Stuart Black[1]

[1] *Department of Geography and Environmental Science, University of Reading, Reading, UK*

[2] *Consejo Nacional de Investigación de Ciencia y Tecnología - Instituto de las Culturas (IDECU), Universidad de Buenos Aires, Buenos Aires, Argentina*

[3] *Cusichaca S.A.C, Cusco, Peru*

[4] *Department of Archaeology, University of Reading, Reading, UK*

[5] *Departamento de Historia del Arte, Universidad de los Andes, Bogotá, Colombia*

[6] *Hydro-GIS Ltd, Chalgrove, UK*

[7] *Quaternary Scientific (QUEST), University of Reading, Reading, UK*

Abstract

Climate variability has had a marked influence on water availability, traditional farming (agro-pastoral) practices, and therefore the livelihood of human communities in the Peruvian Andes since at least the Middle Horizon cultural period (AD 600-1000). Current global climate warming poses a more significant threat, however, enhancing vulnerability and creating a greater risk to all assets. To better understand the challenges faced by rural communities living with climate variability, as well as the opportunities afforded through appropriate adaptive strategies, a research pilot project (ACCESS) was conducted in the Cordillera Blanca and Cordillera Negra, Ancash region. The preliminary findings reveal that variability in precipitation over the past 1500 years was coincident with major cultural changes and advancement in water management practices, although the precise temporal relationships remain uncertain. Nevertheless, the construction of canals and reservoirs, as well as agricultural terraces, clearly indicates that past cultures in the Ancash region recognised the need to enhance resilience and for the sustainable management of natural resources. At the present day, our data indicate that local communities in both Cordilleras are experiencing the effects of climate change, especially water shortages, increasing temperatures and glacier retreat, soil degradation, and greater problems with crop pests. These concerns are worsened by a shortage of agricultural land, conflict between communities and a lack of state intervention. Adaptive strategies proposed by communities include improved water management, economic diversification, greater community collaboration and state investment. The concerns over water availability are in agreement with the preliminary hydrological and crop-water modelling findings of the project, which indicate that with rising temperatures and variable precipitation patterns, improved water management in both cordilleras will be required to maintain effective levels of irrigation for sustainable farming and economic development. Finally, we highlight the importance of restoration of ancient water management and agricultural infrastructure, as well as the significance of indigenous knowledge amongst local communities, as a means of enhancing adaptive capacity in the face of climate change.

Palabras clave: *Climate change, water management, crop water modelling, Cordillera Blanca, Cordillera Negra*

Resumen

En los Andes peruanos, la variabilidad climática ha tenido una marcada influencia en la disponibilidad de agua, en las prácticas agrícolas (agropecuarias) tradicionales y, por lo tanto, en el sustento de las comunidades humanas; al menos desde el período cultural del Horizonte Medio (600-1000 d.C.). Sin embargo, el actual calentamiento global supone una nueva mayor amenaza, ya que hace aumentar la vulnerabilidad y todos los riesgos asociados al cambio climático. ACCESS fue un proyecto piloto de investigación, llevado a cabo en la Cordillera Blanca y la Cordillera Negra de la región de Ancash, con el objetivo de estudiar y comprender los desafíos a los que se enfrentan las comunidades rurales que sufren esta variabilidad climática, y las oportunidades y estrategias adecuadas de adaptación a este fenómeno. Los hallazgos preliminares del proyecto revelan que, durante los últimos 1500 años, las variaciones en las precipitaciones coincidieron con importantes cambios culturales, y avances en las prácticas de gestión del agua; aunque las relaciones temporales precisas son aun inciertas. Aun así, la construcción de canales, embalses y de andenes agrícolas, indican claramente que las culturas del pasado, en la región de Ancash, reconocieron la necesidad de mejorar su resiliencia y el manejo sostenible de los recursos naturales. Los datos resultantes del proyecto indican que, actualmente, las comunidades rurales de ambas Cordilleras están experimentando los efectos del cambio climático, especialmente en relación a la escasez de agua, el aumento de las temperaturas y el retroceso de los glaciares, la degradación del suelo agrícola, y las plagas de los cultivos. Estos problemas se ven agravados por la escasez de tierras agrícolas, los conflictos entre las comunidades, y la falta de intervención estatal. Las estrategias de adaptación propuestas por las comunidades incluyen una mejor gestión del agua, la diversificación económica, una mayor colaboración comunitaria, y más inversión estatal. La preocupación de las comunidades respecto a la disponibilidad de agua, concuerda con los datos y conclusiones preliminares de modelado hidrológico y de cultivos/agua del proyecto. Estos indican que el aumento de las temperaturas, y de los patrones variables de precipitación, harán necesaria una mejor gestión del agua en ambas cordilleras, para mantener niveles efectivos de riego y conseguir una agricultura y un desarrollo económico sostenibles. Finalmente, se destaca la importancia de la recuperación de las antiguas infraestructuras agrícolas y de gestión del agua, y del conocimiento tradicional indígena entre las comunidades locales, como medios para mejorar su capacidad de adaptación frente al cambio climático.

Palabras clave: *Cambio climático, manejo del agua, modelaje del agua de los cultivos, Cordillera Blanca, Cordillera Negra*

Introduction

The current and future impact of global climate change on the major weather systems of Peru remain to be fully understood although it is widely recognised that the dynamics of the South American Summer Monsoon (SASM) and the Intertropical Conversion Zone (ITCZ) may be severely affected as well as the frequency and amplitude of the El Niño Southern Oscillation (ENSO) (Grimm and Zilli, 2009; Vuille et al., 2012). Currently, during the wet season (austral summer – December to March) in Peru, precipitation is at its maximum due to a deep zone of convection in southern Amazonia and strong easterlies. In contrast, during the dry season (austral winter – April to November), the main zone of convection has moved north resulting in a sustained period of lower precipitation (Garreaud et al., 2009; Grimm and Zilli, 2009). Continued warming of the Northern Hemisphere and Atlantic Ocean however may weaken the SASM, which could have a significant impact on the environment, economy and society of the Peruvian Andes because of the profound influence it has on water availability and quality, traditional farming (agro-pastoral) practices, and the livelihood of local communities, amongst many other things (Bird et al., 2011). Increased variability and reduced predictability of water resources (both spatially and temporally) is therefore of considerable concern coupled with the impact of accelerated glacier retreat (in some areas) and the increased likelihood of catastrophic events (e.g., GLOF) that are hazardous to both human communities and the environment.

To better understand the challenges being faced by communities living with enhanced climate variability, as well as the opportunities afforded through appropriate adaptive strategies, we conducted a pilot project funded by the British Academy Knowledge Frontiers programme (Adaptive Capacity of Farming Communities to Climate Change in the Peruvian Andes (ACCESS)). The geographical focus of the research was the Cordillera Blanca (CB) and Cordillera Negra (CN) in the Ancash region of northern Peru (Figure 1). The present-day agro-pastoral system in Ancash has its foundations in pre-Hispanic cultural development and the transformation of the landscape through sophisticated, highly organised engineering including agricultural terraces and water management infrastructure. However, whereas in the pre-Hispanic, Spanish Colonial and early Republican past integrated socio-regional control was paramount to the sustainability of this agro-pastoral system, in the present-day, an apparent lack of investment makes local communities highly vulnerable to external forcing factors, especially climate change. For example, according to several local communities, strategies for water management employed by Peruvian institutions appear to ignore local cultural and agricultural knowledge, which reflects the long history of human occupation in Ancash. Indeed, the archaeological record suggests that the problems being faced in the CN and CB today have parallels with the challenges experienced by communities in the past, which provides an opportunity to better understand how adaptive capacity in the present-day can potentially be enhanced by learning from ancient practices. A major challenge for local communities, policymakers, government institutes, non-governmental organisations (NGOs) and universities in the region, however, is how to unite these diverse sources of knowledge in a way that makes best use of ancient, traditional practices, local knowledge, modern approaches and scientific expertise.

Our methodology was therefore designed to: (1) evaluate ancient water management systems and cultural development in the context of past climate variability over the past 1500 years; (2) characterise the challenges and opportunities due to climate change faced by present-day communities practising agro-pastoralism; (3) provide insight into current water availability and demand, and to identify areas of future water stress. This was carried out at representative sites in both study areas (Figure 1). Here we present a summary of the preliminary findings. We end with a comment on the important role that restoration of ancient water management and agricultural infrastructure can potentially play in climate change adaptation.

Synthesis of Past Climate Variability

Over the past 40 years, there has been a growing body of palaeoclimate data for the Peruvian Andes spanning the last 1500 years from a range of archives (e.g., ice cores, cave speleothems, lake and marine sediments, glacial landforms, peat bogs and archaeological records). Proxy records from these archives have highlighted their sensitivity to atmospheric and oceanic dynamics of tropical South American climate over various timescales (e.g., Haug et al., 2001; Chepstow-Lusty et al., 2003; Rein et al., 2005; Vuille et al., 2012; Apaéstegui et al., 2014;

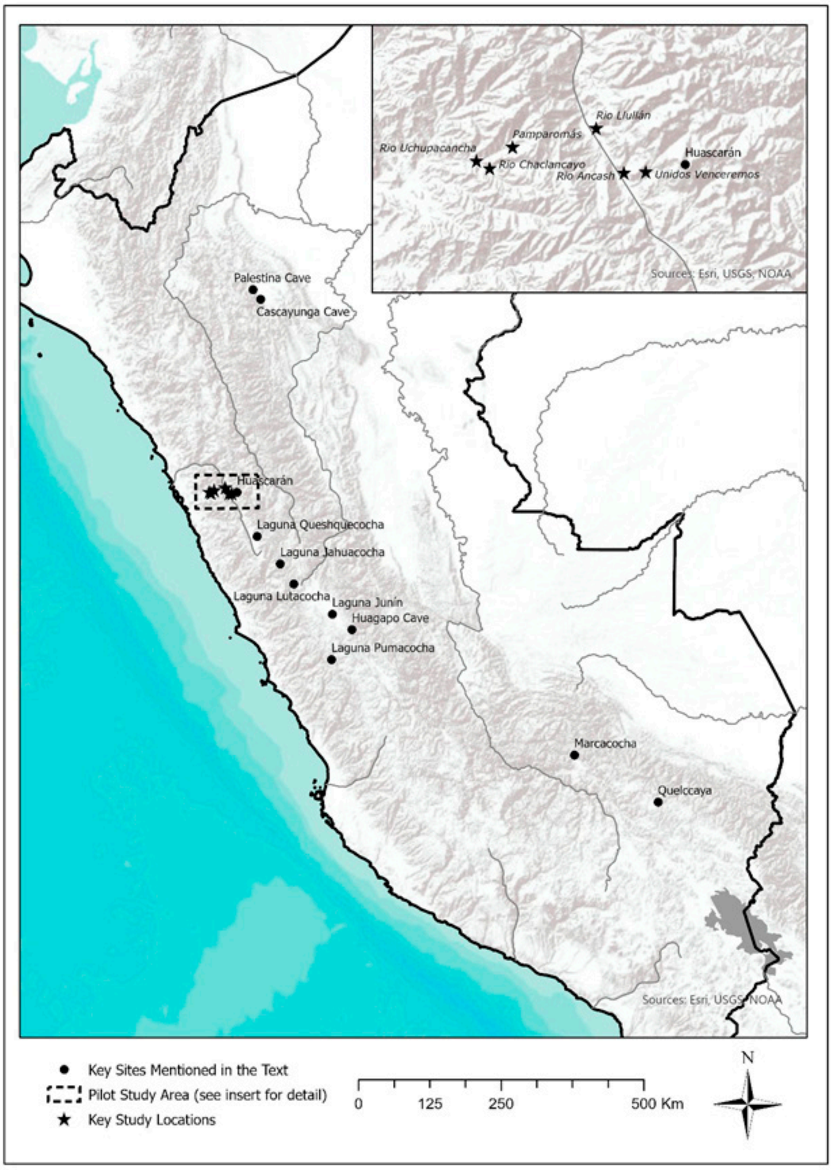


Figure 1. Location of key sites in Peru mentioned in the text. Pilot study area for the ACCESS project highlighted with insert showing the location of Unidos Venceremos, Río Llullán and Río Ancash (Cordillera Blanca), and Pamparomás, Río Chaclancayo and Río Uchupacancha (Cordillera Negra).

Stansell et al, 2017; Thompson et al., 2017; Sandweiss et al., 2020). Records have revealed important episodes of both climate change and enhanced variability such as the Medieval Climate Anomaly (MCA; AD 900-1250), Little Ice Age (LIA; AD 1400-1850) and Common Warm Period (CWP; AD 1850 to present), as well as ENSO events. These records were mainly characterised by changes in the hydrological cycle leading to variability (spatially and temporally) in precipitation due to the intensity of the SASM. Indeed, various studies have highlighted the varying influence of Northern Hemisphere temperatures, tropical Atlantic and Pacific sea surface temperatures (SSTs), the Atlantic Multidecadal Oscillation (AMO) and the position of the ITCZ on the strength or weakness of the SASM over decadal to centennial timescales. On interannual timescales, SSTs in the Pacific also appear to have had a considerable effect on moisture flow over the Andes due to the influence of ENSO resulting in either a rainfall deficit (positive ENSO - El Niño) or surplus during a negative ENSO (La Niña).

Here we provide a synthesis of some of the key changes during the last 1500 years in the Peruvian Andes, with a focus on the MCA and LIA, as the basis for discussion about the possible impact of climate variability on past water availability, its management and the socio-economic structures of human communities (see below). High-resolution speleothem δ^{18}O data from a number of caves have provided compelling evidence for Late Holocene climate change in the Peruvian Andes. At Huagapo Cave, the δ^{18}O data indicate intensification of the SASM during the Middle to Late Holocene transition (Kanner et al., 2013), which is supported by the δ^{18}O ice core record from Huascarán (Thompson et al., 1995), and δ^{18}O lake sediment data from Laguna Junín (Seltzer, Rodbell and Burns, 2000) and Laguna Pumacocha (Bird et al., 2011) (Figure 2). During the Late Holocene, the Huagapo Cave data also suggest good agreement with the Pacific marine record indicating that variability in precipitation was consistent across a wide geographical area, and at times linked to intensification of ENSO and a weaker monsoon (Kanner et al., 2013).

From AD ~1100-1300, data from the Quelccaya ice core indicate that annual net accumulation was below average and that δ^{18}O values were variable and enriched (heavier) by comparison to average values of the last 1800 years (Thompson et al., 2013, 2017) (Figure 2). Given that the record from Quelccaya provides an indication of δ^{18}O variability during the wet season when most of the precipitation occurs in the region due to the SASM, these data indicate that the MCA was clearly a period of much lower precipitation from AD ~1100-1300. Authigenic calcite δ^{18}O values from Laguna Pumacocha (Bird et al., 2011) also suggest that the SASM was less intensive at this time, whilst δ^{18}O values from Palestina Cave (spanning the last 1600 years) similarly show enrichment from AD 920-1100, including a distinctive "double peak" at AD ~934 and AD ~1039 (Apaéstegui et al., 2014). Elevated values were also recorded at AD 421-580 and AD 722-820 at Palestina Cave, which suggests reduced SASM intensity during an otherwise sustained period of higher precipitation prior to the onset of the MCA at AD 920 (Figure 2). Apaéstegui et al. (2014)

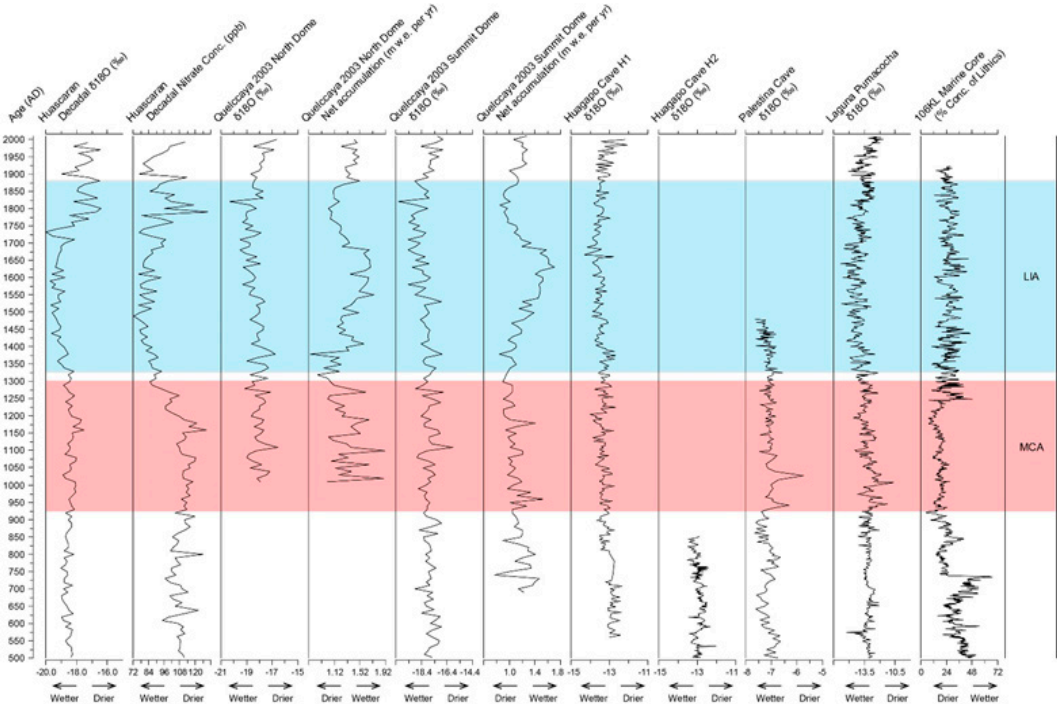


Figure 2. Selected palaeoclimate proxy data for Peru (see text for citation). Maximum age ranges for onset and termination of the Medieval Climate Anomaly (MCA, pink) and Little Ice Age (LIA, light blue) shown as shaded areas. Age model in calendar ages AD. Wetter / drier shifts shown by arrows for each record. Data downloaded from the National Oceanic and Atmospheric Administration (NOAA), USA Department of Commerce (https://www.noaa.gov/).

note that the Quelccaya record similarly shows enriched δ^{18}O values at AD 990 and AD 1080, although whether these are the same events recorded at Palestina Cave and Laguna Pumacocha remains unclear, but they confirm periods of significantly less precipitation. It is suggested that reduced moisture over the Andes during the MCA may be due to higher SST in the tropical Atlantic and a more northerly position of the ITCZ over multi-decadal timescales. Interestingly, Apaéstegui et al. (2014) highlight that at Palestina Cave reduced rainfall during the wet season and correspondingly higher rainfall during the dry season may possibly explain the pattern of δ^{18}O values observed; this implies that during the main growing season for crops in the Andes, higher water availability would not have placed considerable stress on cultivation practices but may have required careful management due to reduced rainfall in the wet season. Marine sediment records off the coast of Peru similarly indicate a period of climate change during the MCA (Rein et al., 2005). These studies, based on sedimentological, alkenone and chlorin analyses, were interpreted as weakening of the ENSO signal from AD 800-1250 and a period of extreme drought preceded and followed by major flood events (Rein, Lückge and Sirocko, 2002). Finally, variation in the timing of the onset and termination of the MCA between archives and their climate change proxies has been noted by several studies, but it seems certain that the MCA was underway by AD ~900 in the Peruvian Andes.

The timing of the onset of the LIA varies considerably between archives but collectively they indicate an age range of AD ~1325-1880. This suggests a rather abrupt transition to the LIA following termination of the MCA. At Quelccaya, the onset of the LIA was evidenced by significant changes in geochemistry and a reduction (lighter) in δ^{18}O values from AD ~1520-1880 indicating higher precipitation (Thompson et al., 2013, 2017). Furthermore, the annual net accumulation significantly increased until AD ~1680 but thereafter declined (Figure 2). As noted above, precipitation in the Peruvian Andes is mainly received from the tropical Atlantic via the Amazon Basin, but it is believed that on interannual timescales SSTs in the Pacific have a considerable effect on moisture flow over the Andes influencing δ^{18}O values. This suggestion appears to be consistent between the findings from the Quelccaya, Huascarán and Sajama (Bolivia) ice core records, and collectively indicates that δ^{18}O values do also reflect SSTs in the Pacific, ENSO variability and migration of the ITCZ, despite agreement that the SASM is the primary source of moisture (Thompson et al., 1995). During the LIA, ice core geochemistry, especially higher nitrate and ammonium values, from Quelccaya also suggest higher precipitation, whilst depleted δ^{18}O values indicate lower SSTs and cooling. If these reflect Pacific SSTs and linked ENSO events, then they undoubtedly resulted in glacier mass gain, which is consistent with the higher annual net accumulation reported for Quelccaya from AD ~1520-1680 and therefore glaciological evidence for a cool and humid climate. This was succeeded by warmer and drier conditions and glacier retreat from AD ~1680-1880.

These ice core records for higher precipitation during the LIA (intensified SASM) appear to be consistent with speleothem δ^{18}O values for a 20% increase in rainfall compared to the 20th century (Reuter et al., 2009), and those from authigenic calcite δ^{18}O from lake sediments (Bird et al., 2011). At Palestina Cave, depleted δ^{18}O values were recorded at AD 1325–1820, with the lowest values from AD 1400-1593, which represents a longer time series of climate variability during the LIA than obtained from Quelccaya (Apaéstegui et al., 2014) and may also suggest complex spatial variability in LIA precipitation in the Peruvian Andes at this time (Figure 2). Similar depleted δ^{18}O values were noted at AD 580-720 and AD 820-920, which confirm higher SASM intensity at times prior to the onset of the MCA. At Huagapo Cave, a gradual decrease in δ^{18}O values was also recorded from AD 1365-1820, which is consistent with those from Palestina Cave (Kanner et al., 2013). Both Huagapo Cave and Cascayunga Cave δ^{18}O values provide clear evidence for the LIA, which is considered to reflect a period of considerably higher precipitation and variability in the tropical Atlantic (both SSTs and AMO) with higher moisture levels attributed to cooler tropical Atlantic SSTs (Reuter et al., 2009).

Data from Lagunas Queshquecocha, Jahuacocha and Lutacocha, coupled with glaciological evidence from nearby landforms, similarly noted that during the MCA glaciers retreated, resulting in lower clastic sediment input to the lakes (Stansell et al., 2013). In contrast, during the LIA glacier re-advance was evidenced by increased clastic sedimentation from AD ~1400/1500 (Stansell et al., 2017). At Laguna Pumacocha, δ^{18}O values indicated reduced precipitation from AD 900-1100 (MCA) and again from AD 1900, whilst from AD 1400-1820 there was significantly increased precipitation during the LIA (Bird et al., 2011), reflecting changes in the SASM. Interestingly, at Laguna Marcacocha, Chepstow-Lusty et al. (2003) also provided compelling evidence based on pollen records for drier episodes at AD 100 and AD 550, with an extended dry phase from AD 900-1800 during the MCA that extended into the LIA, which may further highlight regional or site-specific sensitivity to climate variability. Finally, marine sediment records from Peru indicate that between 500-700 years ago (AD ~1300-1500) lithic concentrations increased, probably related to catastrophic flood events, which interestingly coincide with the records presented above from the Andes for higher precipitation (Rein et al., 2002). These marine data suggest possible increased frequency of ENSO events from the beginning of the LIA onwards (Figure 2).

Past Climate Variability and Cultural Change

Water is a critical human resource in the present, as well as it was in the past. Throughout the pre-Hispanic period, cultural transformations were defined by how different cultures managed and harnessed water (Kosok, 1965; Lane, 2006, 2014; Ortloff, 2010). In this regard, our study area stretches across two cordilleras from the

Cordillera Blanca's (CB) Huandoy glacier (6356 m a.s.l.) to the foothills of this mountain range, encompassing the Ancash, Llanganuco and Llullán river basins (Figure 1). These high energy streams flow into the section of the Santa River sandwiched between the Cordillera Negra to the west and Cordillera Blanca to the east, a major inter-Andean valley, also known as the Huaylas callejón or corridor. Further east rises the glacier-denuded Cordillera Negra (CN), from the high peak of Cerro Rico (5004 m a.s.l.) down the Chaclancayo (also known as Huarac Pampa) and Uchupacancha river basins, down to the coast and the Pacific Ocean (Figure 1).

The CB and the CN are a study in contrasts. While glaciers have been a permanent feature of the CB since at least the Pleistocene, the CN has been mostly stripped of permanent ice cover for most of this same period (Mark and McKenzie, 2007; Stansell et al., 2017). Indeed, aside from the Cordillera la Viuda in central Peru (Olarte Navarro, 2007), the whole of this Pacific-facing mountain range nowadays relies exclusively on seasonal rainfall and winter sea-fog (garúa) for hydrological replenishment. Given the fact that most of this precipitation comes from the Amazon Basin through strong easterlies pushing into the Andes during austral summer rains (December to March) (Garreaud et al., 2009), it is of little surprise that annual precipitation tends to be considerably lower in the CN (c. 500 mm) than in the CB (c. 1000 mm) (Tremolada et al., 2008). Therefore, not only does the CN not benefit from glacier runoff, but it is also considerably drier than the other mountain ranges in the region. This has shaped past human responses to water across both cordilleras, responses with important repercussions for today's increasing water insecurity across the region.

Extensive archaeological survey and excavation by our team (1999-2021) have revealed evidence of continuous settled occupation of the area since the late Formative Period or terminal Early Horizon, c. 200 BC, and previous excavations in the area attest to the presence of hunters and early farmers as far back as 10,000 years ago (Lynch, 1971). Beginning with settlement on the deep rich soils on the valley floor, the farming landscape gradually filled in with settlements at water sources and along routes across the glaciated mountains. Overall, a number of important shifts in settlement patterns are apparent in the area, occurring during the late Middle Horizon (AD 800-1000), the Late Intermediate Period and Late Horizon (AD 1000-1400 and AD 1400-1532 respectively) and the early Spanish Colonial Period (AD 1532-1615). Settlement shifts which have important connotation in regards to water management systems.

Therefore, while hydraulic technology is common to both cordilleras, the level of investment in the drier CN was of considerably more magnitude given the greater water exigencies prevalent in this mountain range. That said, irrigation canals are ubiquitous to the Andes, in use since at least the Fifth Millennium BC (Dillehay, Rossen and Netherley, 1997), serving to transport water from source to where it is required in the most efficient manner possible (Denevan, 2001: 146). In our study area, most canals tend to be local affairs moving water short distances from glacier outflow, rivers, and basins to nearby fields and pastures. Larger canals, such as the Huiru Catac in the Jimbe Valley were probably late pre-Hispanic or Inca (AD 1400-1532) mega-projects aimed at supplying water to the coast (Maza, 2017). In many cases in the pre-Hispanic past, canals were associated with terraces (Denevan, 2001: 141), although in the study area most terraces have long been abandoned or destroyed to allow animal (mainly oxen and mules) traction ploughing of larger fields. In the vertiginous slopes of the study area, this has led to considerable soil erosion.

Across the research area ancient gravity irrigation canals, many of which are still in use, denote significant coordinated investment of labour for agriculture. Large acequias madres (primary canals) criss-cross both the CB and CN, some of them as rock cut canals similar to those found at Cumbemayo, Cajamarca, suggesting Early Horizon (1200-100 BC) use of this type of technology in the area. Likewise, in the higher areas of the CB, several canals transport water from glacial basins to their drier neighbours. In turn, this water is also used to replenish wetland areas – such as Huarca (near Yungay) – all indicative of a sophisticated hydraulic technology employed in both agriculture and herding. Evidence of repair, erosion, and changes in the form of the canal at the Middle Horizon (AD 600-1000) site of Keushu, for instance, suggests intensified water resource use during this period (Herrera, 2017: 216), but due to uncertainty over the precise timing of construction of these canals it remains unclear whether this was a response to enhanced water availability prior to the MCA, or reduced water during the MCA.

Indeed, the Middle Horizon (AD 600-1000) was crucial for the development and expansion of water capture technology across the Andean highlands, although it remains uncertain whether this expanded after the start of the long dry period (AD ~900; see above, also, Ortloff, 2010: 57-59) associated with the onset of the MCA. In our study area, we hypothesise that the CN led the way in hydraulic technology expansion throughout this end phase of the Middle Horizon and the subsequent Late Intermediate Period (AD 1000-1400), attempting through various engineering constructions to assuage incipient and incremental water insecurity. Greater precipitation, and generally colder conditions, in the period after AD 1325 with the onset of the LIA does not coincide with an appreciable increase in hydraulic technology use either in the CB or CN. Nevertheless, this subsequent period of the LIP until the Inca conquest during the early 15th century was marked by heightened levels of internecine violence and the construction of easily defensible hilltop settlement sites across the highlands (Arkush and Tung, 2013). Ethnohistoric and palaeoenvironmental evidence, though, does posit an important change in baseline economics with increasing investment in camelid herding over farming in the highlands, which continued under the Inca (AD 1400-1532) (Chepstow-Lusty, 2011; Duviols, 1973).

Overall, the expansion in water technology throughout this whole period was also conducted against the backdrop of an ever-increasing human population, which reached its apogee shortly before the arrival of the Spanish in AD 1532 (Cook, 1981). Technological expansion and innovation came in the form of water dams, reservoirs, artificially irrigated wetlands using check-dam type silt-traps known as silt dams and reservoirs, terraces, canals, and other associated hydraulic infrastructure, sustaining a technologically savvy, highly specialized and integrated agro-pastoralist economy. The ensuing hydraulic landscape transformation enabled the storage of water both physically and geologically on a whole-of-basin or -tributary basis (Lane, 2017). There was also investment in hydraulic engineering in the CB, even if this entailed less large upland dams, given the prevalence of natural lakes and glacier meltwater, and more reservoirs and canals ensuring water availability to farming and herding areas.

Importantly, during the LIP all this infrastructure was managed at a community and village level (respectively the *ayllu* and *llacta/marca*) by corporate groups rather than well-established hereditary elites (Lane, 2009). Later incorporation of all this region into the Inca Empire (c. AD 1450) brought with it modifications to the hydraulic system while maintaining much of the underlying socio-economic lifeways, beyond perhaps a certain shift towards greater societal hierarchy, including the emergence of potentially hereditary *curaca* or chiefs (Aibar Ozejo, 1968). At this stage in the late pre-Hispanic period (and throughout much of the 16th century) this region, the Inca province of Huaylas, was one of the richest and most populous of the Andes (Levillier, 1926: XIII: Segunda Parte: 308-9). A prosperity based essentially on a persistence of small-holder subsistence agriculture that continues altered but unabated, at least in the CN, up to the present (Rasmussen, 2015). The CB is different given that continued recourse to water, and indeed increased water availability due to glacier retreat and enhanced meltwater flow, has led to evermore market-orientated initiatives, such as export quality flower-growing, with the potential environmental and social problems that this brings in its wake (Orlove, 2020).

Spanish conquest impacted heavily on the Andes and in the Huaylas region, through the triple ills of disease, dislocation and depopulation. Severe depopulation through deadly European diseases and community dislocation caused upwards of a 60% reduction in population during the first 100 years of contact (Cook, 1998) and the whole region entered into a downward spiral from which it only slowly emerged during the 20th century. In this context, the rich suite of hydraulic engineering that had met local needs during the pre-Hispanic period was abandoned wholesale such that it was mainly only canals which were up-kept. Indeed, it is relatively recently that a buoyant human population coupled with the exigencies of modern life and climate change are gravely stressing local resilience and water security. Yet, modern populations and governments seem ill-equipped to mitigate against ever-increasing water stress even when the area is replete with potentially re-usable pre-Hispanic installed hydraulic capacity in the shape of water dams, reservoirs and relict terraces. Only new thinking that incorporates modern solutions, such as drip irrigation, and rehabilitates old technologies has a chance of meeting people's needs in the short-term, while guaranteeing water security in the medium- and long-term.

Climate Change: Challenges and Opportunities for Farming Communities

Andean mountain ecosystems are much affected by climate change (Torres, Frías and de la Torre, 2014; Schoolmeester et al., 2016; Duputis, 2021), especially in relation to water availability and agriculture, which is the main economic activity of local indigenous communities, so they are very vulnerable to this phenomenon (USAID, 2011; Pramova, di Gregorio and Locatelli, 2015). This is the case of the Cordillera Blanca (CB) and Cordillera Negra (CN), where abundant studies on the impact of climate change have been conducted (Carey, French and O'Brien, 2012; McKinney, Anderson and Byers, 2011). The research of the ACCESS project in these cordilleras included an important social science dimension, designed to integrate the socio-economic context with local knowledge and cultural characteristics of rural farming communities, by exploring the ideas and perceptions of members of the communities about their agricultural systems and problems of living with climate change. This is important because local and indigenous knowledge and traditions are key to climate change adaptation, in the Andes and beyond (Valdivia et al., 2010; Kirkland, 2012; Walshe and Argumedo, 2016). The pilot research was mainly based on ethnographic fieldwork conducted by the project members (summer 2019), involving participatory workshops and interviews following a methodology known as RAAIS (Barrett et al., 2017; Schut et al., 2015) (Figures 3A and 3B). In the CB, fieldwork focused mainly on the peasant community of Unidos Venceremos (near Yungay), while in the CN we focused on the peasant community of Pamparomás (see https://arcg.is/0rLeXm [English version]; https://arcg.is/19yWum [Spanish version]) (Figure 1).

Our preliminary findings indicate that both cordilleras are dominated by the presence of what is known as peasant communities, formerly called indigenous communities, which have a special legal status based on distinctive communal features (e.g., ownership of their territories) (Ferreira, 2012). In these communities, all local families own land and work in agriculture, which tends to be their main economic activity, complemented with other sources of income (e.g., working in shops, taxi services and temporary migration). Agricultural production in these communities is partially used for self-consumption (traditional crops such as maize and potatoes in both study areas), and partially oriented to the market economy (e.g., flowers and greenhouse fruit in the CB) due to their proximity to coastal and urban areas. In contrast, the main river valley (Río Santa) that separates

Figure 3. A selection of photographs taken during the field investigations. A. Workshop at Universidad Nacional Santiago Antúnez de Mayolo (Huaraz). B. Workshop at Pamparomás village (CN) with the Junta de Desarrollo Distrital de Pamparomás. C. Canalised edge of the Huarca wetland (CB) supplying irrigation water. D. Modern reservoir in the Río Uchupacancha (CN). E. Flow gauging in the Río Uchupacancha (CN). F. Pre-Hispanic water dam of Ricococha Alta (CN).

both cordilleras (Callejón de Huaylas) is dominated by the presence of cities, towns and semi-rural areas, where land tenure and agro-pastoral work are based on full private property. Many people living there, including those in urban centres, tend to own or have access to some rural land, and to work to some degree in agriculture, as a complementary economic activity. Other important economic activities in the area are tourism (attractive because of the snow-capped mountains and glaciers) and mining, which has an important environmental cost. As a result, the Ancash region is comparatively wealthier than others in the Peruvian Andes (latest figures from Instituto Nacional de Estadística e Informática del Perú (www.inei.gob.pe/): national poverty rate 20.5% in 2018; Ancash 22.0% compared to Cusco 25.0% and Ayacucho 51.5%). In the CB peasant communities are comparatively better off, as water is more abundant because of the presence of glaciers and due to glacier retreat (Raymondi, Delgado-Arias and Elder, 2012). Therefore, agriculture is more productive and more profitable, allowing greater investments in infrastructure (e.g., greenhouses, technified irrigation). There are also more economic opportunities related to tourism and other activities. In the CN, communities are comparatively poorer because water is scarcer and agriculture less productive, and there is less diversity in local economies, so less profits and investment.

Within each study area, our research has identified the following main socio-economic and environmental challenges, which are deeply interrelated (Tables 1 and 2). **Lack of water for agricultural use:** Most sources highlighted this as the most important challenge for local peasant communities. This has been a long-term problem in this and in other Andean areas, although it has worsened in recent decades due to decreasing precipitation and more irregular weather conditions, including an increasing number of extreme events (e.g., prolonged and harsh frosts). **Increasing temperatures and glacial retreat:** Most sources also agreed that the acute increase in temperature in recent years is one of the main challenges for local agriculture. This has contributed to increasing aridity and impoverishment of agricultural soils, which are less productive and need more irrigation as a result. It has also contributed to gradual changes in local production areas and ecological zones, marked mainly by altitude, which have had a direct effect on local agriculture, with an upwards movement of ecosystems, crops and also an increase in crop pests (as reported in other Andean areas e.g., Skarbø and Lambrou, 2015).

Soil degradation, pests and agrochemicals: The increasing degradation of agricultural soils and crop pests in the agricultural areas has contributed to the increased use of agrochemicals (fertilisers, insecticides and herbicides). The long-term impact on soil heath is currently unknown. **Lack of agricultural land for local families:** Successive plot subdivisions through inheritance reduces families' access to agricultural land. As a result, families and individuals, mostly youngsters, who have not enough land and have to look for complementary economic activities (e.g., commerce, daily waged labour) or are forced to migrate. The latter contributes to the higher age range of the remaining population and, sometimes, to workforce shortages for agricultural work. **Conflicts within and between local communities, and weakening of social bonds and cohesion:** The lack or insufficiency of natural resources (e.g. land, water), and the resulting competition for them, has been a source of internal and external conflicts and competition within and between local communities, which has been increasing in recent years. This takes place between local families and sectors, between neighbouring communities, and between communities and other actors (e.g., mining companies). Most of these conflicts involve water, land or environmental problems (e.g., contamination, pollution). Older farmers also pointed to the weakening of social bonds and cohesion within communities as an emerging problem, as a result of an increasing materialism and individualism among the young, and of an increasing disrespect towards older generations.

Lack of state intervention: Most farmers also pointed to the role of the state as an important factor in local agriculture, mostly in negative terms. At a general level, many criticised the negligence of the state towards Andean areas and rural communities, and its lack of interest and support for small-scale agriculture. Specifically, they criticised state intervention in their communities as insufficient, inefficient and affected by problems such as widespread corruption, discoordination between different levels (national, regional, local) and political interests. They were demanding more and better support by the state.

Table 1. Ranking of main agricultural challenges and opportunities identified by local farmers in the fieldwork's workshops according to their importance: Cordillera Negra (workshop conducted in Pamparomás on September 6, 2019).

A. Challenges-problems	B. Solutions-opportunities
a.1. Very important 1. Lack of water for agriculture 2. Irregularity of rains 3. Increasing temperatures 4. Droughts 5. Lack of state support 6. Mining-related contamination 7. Increasing plagues and pests	**b.1. Very important** 1. Improvements in collaboration and unity (social cohesion) in local communities 2. Improvement of state intervention and coordination 3. Dam ponds and lakes in high areas 4. Reforestation 5. New technologies for storing water (e.g., filtration ditches) 6. Construction of reservoirs for rainwater harvesting 7. Improvement of local communication and access (roads, paths, etc.)
a.2. Important 1. Degradation of soils in agricultural lands 2. Loss of social unity (cohesion) within local communities 3. Lack of coordination between agriculture and herding 4. Lack of combination of ancient and traditional technologies with modern ones and science 5. Use and abuse of agrochemicals	**a.2. Important** 1. Improvement in general planification (agriculture, etc.) 2. Technified irrigation combined with traditional technologies 3. Improvement of agropastoral training and formation 4. Increase economic diversification (to avoid migration, etc.) 5. Better organisation and management of river basins 6. Limit and reorganise herding in high areas
a.3. Less important 1. Lack of efficient agropastoral training 2. Migration of local youngsters 3. Need to introduce improved livestock breeds 4. Frosts	**b.3. Less important** 1. Tourism 2. Installation of greenhouses (in lower areas) 3. Set up associations of agricultural producers

Within each study area, our preliminary research has identified the following main socio-economic and environmental opportunities and possible solutions

Table 2. Ranking of main agricultural challenges and opportunities identified by local farmers in the fieldwork's workshops according to their importance: Cordillera Blanca (workshop conducted in Huaraz on September 9, 2019).

A. Challenges-problems	B. Solutions-opportunities
a.1. Very important 1. Increasing temperatures 2. Glacier retreat 3. Lack of water for agriculture 4. Irregularity of rains 5. Degradation of soils in agricultural lands 6. Use and abuse of agrochemicals 7. Lack of support by the state 8. Increasing plagues and pests	**b.1. Very important** 1. Construction of reservoirs for rainwater harvesting 2. New technologies for storing water (e.g., filtration ditches) 3. Technified irrigation combined with traditional technologies 4. Improvement of state intervention and coordination 5. Improvement of education 6. Tourism 7. Reforestation 8. Better organisation and management of river basins
a.2. Important 1. Droughts (increasing and worsening) 2. Lack of combination of ancient and traditional technologies with modern methods and science 3. Mining-related contamination 4. Lack of efficient agropastoral training 5. Frosts (increasing and worsening) 6. Loss of social unity (cohesion) within local communities	**a.2. Important** 1. Improvement of local communication and access (roads, paths, etc.) 2. Improvement of agropastoral training and information 3. Improvement in general planification (agriculture, etc.) 4. Increase economic diversification (to avoid migration, etc.) 5. Improvements in collaboration and unity (social cohesion) in local communities
a.3. Less important 1. Need to introduce improved livestock breeds 2. Agroindustry 3. Migration of youngsters	**b.3. Less important** 1. Dam ponds/lakes in high areas (when they are not in protected spaces) 2. Limit and reorganise herding in high areas 3. Set up associations of agricultural producers 4. Installation of greenhouses (in lower areas)

(Tables 1 and 2). **Water supply for agricultural use:** Most local sources pointed to technified irrigation (through aspersion stationary processes [for flowers in the CB] or drip irrigation [for fruit in the CB]) as the main solution to the lack of water. However, they recognise that this requires a high level of investment and many families acknowledged that they cannot afford the apparatus, while the state is not investing in such infrastructure. An alternative suggestion was the construction and improvement of infrastructure, such as dams in higher elevation lakes and reservoirs for rain harvesting in strategic locations, although such measures also involve high investment. Some sources highlighted the need to combine modern technology and science with the use of ancient Andean technology and techniques of water supply and management for agricultural use, such as contention ditches, wetlands (*bofedales*) and agricultural terraces. Others highlighted the need to improve the management of river basins and micro-basins in the area as an important source of water for agricultural use.

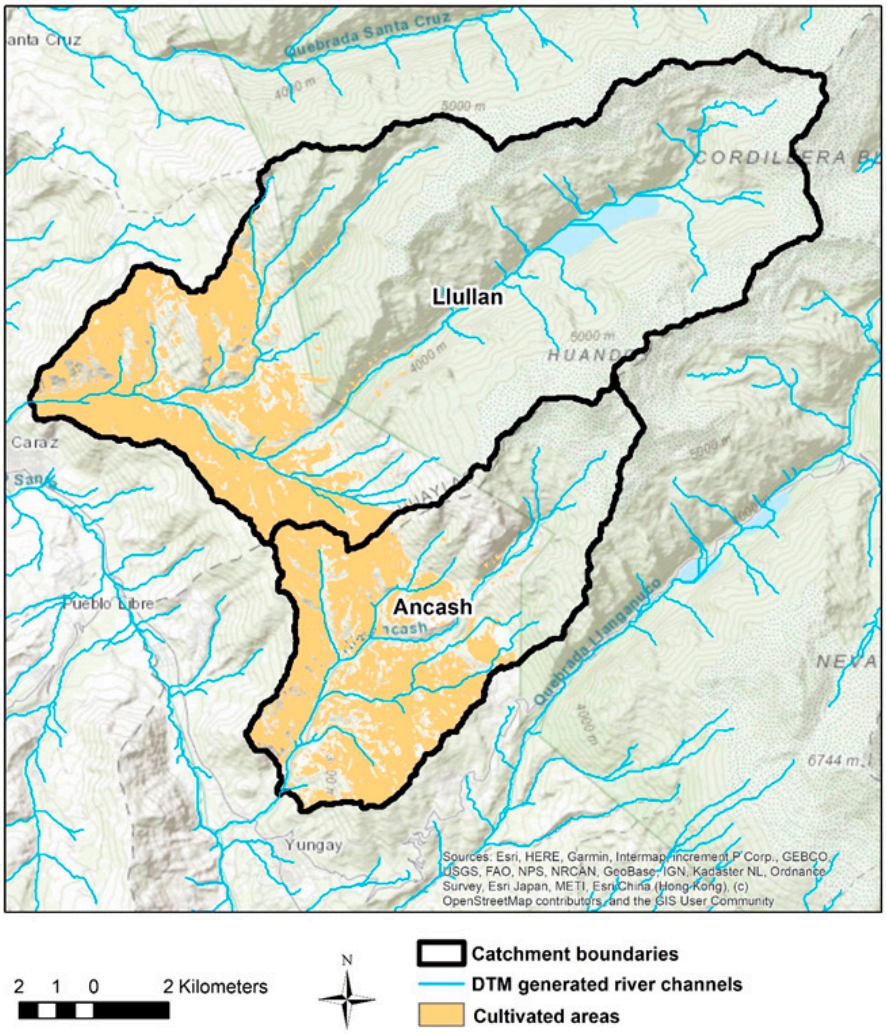
State intervention: Most informants pointed to greater involvement and commitment of the state within Andean areas and agriculture, and of an increase and improvement of state intervention in local communities as a channel to improve their agriculture and address some of its challenges. Particularly, they pointed to the need for more state investment in agricultural infrastructure (e.g., technified irrigation, reservoirs) and training (e.g., agricultural techniques, crops), and the need to increase and improve the coordination and collaboration between state levels (local, regional, national) and programmes in relation to agriculture and environmental conservation. More specifically, they demanded more and better specific training by the state and NGOs about climate change and its repercussions, especially in relation to the future challenges and opportunities for their communities. Economic diversification: One of the alternatives that some sources suggested to tackle agricultural challenges in local communities was to diversify their economic activities, for example enhancing internal commerce, business and tourism. They argued that this would be a way of counteracting their excessive dependence on agriculture, and of creating new opportunities for local people, thus reducing out-migration. Improve collaboration and unity within and between local communities: As commented above, one of the problems that some sources singled out in local communities was the increasing loosening and erosion of social unity and cohesion between their members, and regarding the communal system of peasant communities. Some even considered this as a major threat for the future survival of their communities, and pointed to the need for improving the internal collaboration and unity among members as a way of bettering their socio-economic situation and social cohesion. For agropastoral farming systems, this improvement in internal collaboration would include better coordination between herding and agriculture, and between community sectors for irrigation and the distribution of resources.

Water Availability and Climate Change: Implications for Farming Communities

Water availability from precipitation and irrigation was compared to the crop water requirement in four catchments in the Ancash region to determine whether there was a water surplus or deficit for farming (Figure 1). As such, this hydrological aspect of the overall study aimed to compliment larger scale assessments of water availability and demand in the whole Río Santa catchment (e.g., Aste Cannock, 2018). This is through a nuanced consideration of the impact of present-day and future water availability on the communities living on the mountain slopes above the larger urban centres and more intensive farms of the Río Santa valley floor.

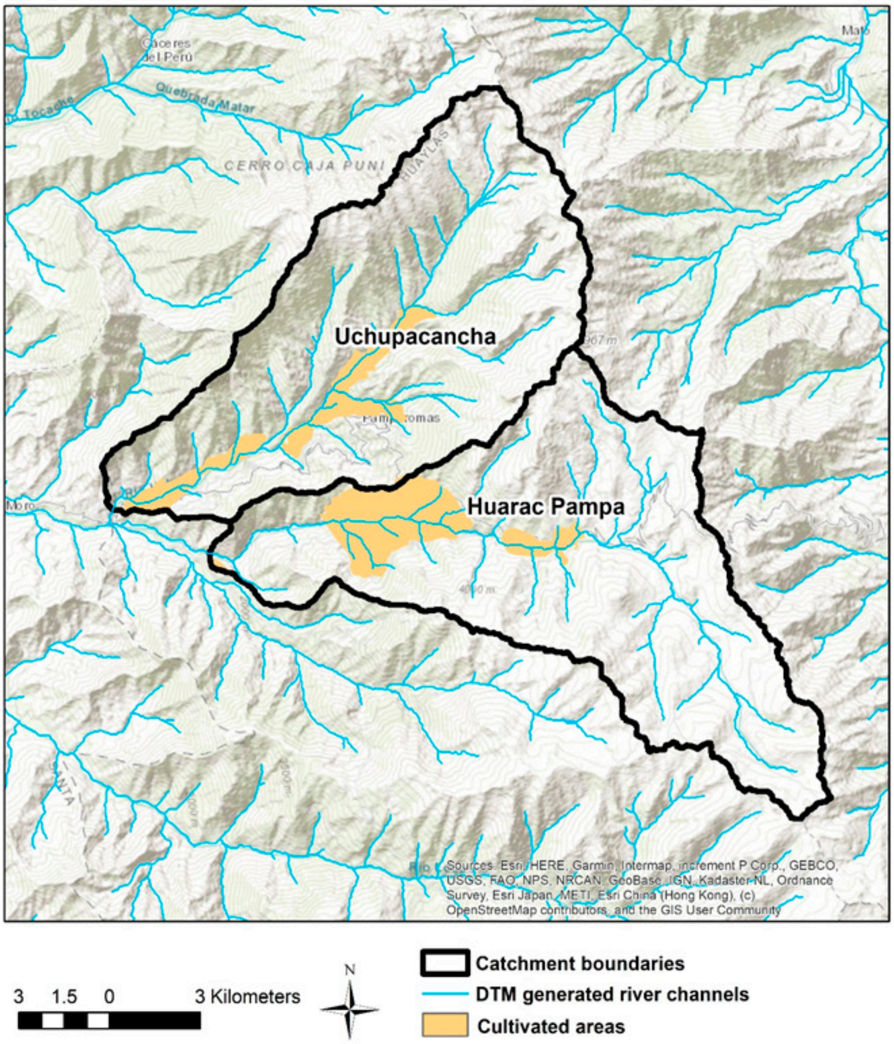
Of the four study catchments, the Río Llullán and Río Ancash are in the Cordillera Blanca (CB) and the Río Uchupacancha and Río Huarac Pampa (Chaclancayo) are in the Cordillera Negra (CN) (see https://arcg.is/0rLeXm [English version]; https://arcg.is/19yWum [Spanish version]) (Figures 4 and 5). All four catchments are relatively small (< 150 km^2) and at elevations above 1400 m a.s.l. In the Río Ancash and Río Llullán, multiple crops are grown all year using the wet season precipitation, which is some 97% of the total, and using inundation and some sprinkler irrigation in the dry season. Air temperature is strongly dependent on altitude, yet relatively constant through the year, which means that the glaciers melt all year producing irrigation water. Melt water, collected in Laguna Llanganuco in the Río Ancash and Laguna Parón in the Río Llullán, supplies the irrigation networks. In the CB, field inundation irrigation takes advantage of gravity and water is fed into ever smaller canals, which are eventually hand-dug to irrigate individual fields. There is some use of groundwater springs, seeps and wetlands but this is very localised (Figure 3C). A large, and as yet unquantified, proportion of the irrigation water flows beyond the lower reaches of the Ancash and Llullán catchments to irrigate farmland adjacent to the Río Santa.

No glaciers exist in the CN study area and water for irrigation is abstracted from streams and wetlands (*bofedales*). The water is stored in reservoirs behind dams in various states of repair at higher elevations and large tanks or reservoirs in the lower valley reaches (Figure



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 4. Details of the topography, drainage and extent of cultivated areas for the Cordillera Blanca study catchments with the outlets at -77.804, -9.035 decimal degrees for the Río Llullán and -77.745, -9.128 decimal degrees for the Río Ancash.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 5. Details of the topography, drainage and extent of cultivated areas for the Cordillera Negra study catchments with the outlets at -78.058, -9.101 decimal degrees for the Río Uchupacancha and -78.030, -9.116 decimal degrees for the Río Huarac Pampa..

3D). In the CB, irrigation coupled with the constant air temperature allows a greater crop variety and productivity and continual growing all year. For this reason, agriculture is more productive and profitable to local CB farming communities, and the communities are comparatively better off than in other areas, such as the CN, where water is scarce. In the CB, the farmers irrigate once every eight days during the dry season. Irrigation channels are used to flood a field before (at least once) and soon after (a few times) planting. Irrigation is managed by committee for different canals. These committees include officers elected democratically on a temporary and rotational basis by local *comuneros* (community members), mostly male heads of families, as part of their communal duties. Therefore, all *comuneros* participate at different stages of their lives in local (and communal) irrigation management.

The available water for crops was quantified through initial field measurements of river and irrigation canal discharge and existing precipitation data (Figure 3E). The crop water requirements were estimated using the Food and Agriculture Organisation CROPWAT (version 8) model which is freely available computer software which uses soil, climate and crop data as inputs (Smith, 1992). Water use, effective rainfall and the irrigation requirement, all expressed in millimetres over the growing season, were estimated for each crop grown in the CB and CN. The variation in crop water requirement with altitude was small so the results for the mean altitude were taken for each crop type, and the crop water requirement was multiplied by the crop area to estimate the total water volume requirement in each catchment. The crop area was estimated from satellite imagery and vegetation mapping. Our community workshop in Huaraz (see https://arcg.is/0rLeXm [English version]; https://arcg.is/19yWum [Spanish version]), and pre-existing mapping of the irrigation canal system in the Río Ancash, allowed the extent of the irrigation canal system to be understood and mapped in part, along with an understanding of the community use of water and irrigation scheduling. The climate change impact on crop water demand and water supply during the 2030s was considered in further CROPWAT simulations by increasing all the air temperatures by 4 °C and assuming a 15% increase in precipitation for the CB and a 15% decrease in precipitation for the CN catchments in line with recent climate change projections for the Ancash region (Obregón et al., 2009).

Overall, our findings suggest that crops are not grown at their potential yield in either high valleys of the CB or CN. In the CB, this is because much of the irrigation water bypasses the high valleys during the dry season and flows downstream to the larger growers on the floor of the Río Santa. In the CN, the yields are low because precipitation is low. Our initial assessment suggests that climate change will make things worse in both the CN and CB. In the CB, an increase in effective rainfall is projected but this does not offset the larger increase in crop water requirements due to higher air temperatures, so irrigation requirements will become higher. In the CN, lower projected precipitation will further reduce the water available for growing. Future research will further detail the mapping of the irrigation system and crops grown to allow refinement of the catchment water balances. At present, regional estimates of crop cultivation areas are assumed representative of the local crop cultivation in the study catchments.

Lessons from the Past: Rural Development Responses to Climate Change

As has been shown throughout this article, climate change has affected Andean communities during several key periods over the past 1500 years. It has also been demonstrated that these communities attempted to adapt to these changes – in particular those relating to prolonged droughts such as the period after AD ~900. Given this, it is worth examining which of these adaptations were successful and which were less so and to see whether certain strategies could be replicated or at least partially so today. The evidence shows that huge efforts were made to improve water related infrastructure such as reservoirs, dams, canals and *amunas* (see below) and to building agricultural terraces on a massive scale throughout much of the highlands and coastal areas by different pre-Hispanic civilizations. A number of NGOs and also governmental organisations working in Peru have been implementing projects to rehabilitate some of this ancient agricultural and hydrological infrastructure, often with very positive results (Junta de Desarrollo Distrital de Pamparomás, 2000; Herrera Wassilowsky, 2012; Herrera, 2017). Some of the best examples include the following.

Asociación Bartolomé Aripaylla (ABA): Located in the community of Quispillaccta in the district of Chuschi in Ayacucho, this organisation is run by a local family and has been very successful in adopting the pre-Hispanic practices of capturing water during the wet season in a series of large and small lakes and reservoirs, some of which have been rehabilitated and some of which have been newly constructed. This water is stored until required for irrigation. **Desco Sur:** This NGO spent many years working in the Colca Canyon in Arequipa, carrying out many different activities including the rehabilitation of 858 hectares of agricultural terraces benefiting nearly 1400 families. **Condesan:** This organisation, with offices both in Peru and Ecuador, is dedicated to the sustainable management of resources and is particularly interested in promoting nature-based strategies. One of their major projects has been the rehabilitation of *amunas* in the community of Huamantanga (Lima region). Here, pre-Hispanic populations constructed a series of canals to take rainwater to areas where the geology allowed the water to flow underground into subterranean deposits. These then filter-down and feed springs located lower down the valley (Duputis, 2021). **Agro Rural:** This governmental organisation ran a pilot project to rehabilitate 150 hectares of andenes between 2011 and 2014 in Matucana in the Lima region, thus benefitting 240 families.

A major part of rehabilitation programs in the Andes has entailed the restoration of terraces or *andenes* (e.g., Llerena, Inbar and Benavides, 2004; Posthumus and de Graaf, 2005; Posthumus and Stroosnijder, 2010; Willems et al., 2021). In this regard, perhaps the best example is the work carried out by **The Cusichaca Trust** from 1977 onwards. The Cusichaca Trust (CT) (a UK based charity) was founded by Dr Ann Kendall initially to carry out archaeological excavations around the community of Chamana at the base of the Cusichaca Valley within the Vilcanota Valley in the Cusco region (Kendall, 2005; Kendall and Rodríguez, 2009). One of the first studies undertaken at Chamana was of the pre-Hispanic agricultural systems located nearby. It was observed that the productive area during Inca times had been greater than at present. One of the main reasons for this was the extensive use of areas of agricultural terraces, which are found throughout the sacred valley. Partly as a result of these studies, both CT and its Peruvian partner **Asociación Andina Cusichaca (AAC)** began to implement a series of rural development projects in Chamana and subsequently in the Patacancha Valley, Ollantaytambo, Cuzco and in the Chicha Soras and Sondondo valleys in the Apurimac and Ayacucho regions (Kendall, Aguirre-Morales and Aramburú, 2006; Kendall and Chepstow-Lusty, 2006).

One of the key goals was the recovery of prehispanic agricultural systems in each valley using primarily the original methods and materials (Kendall, 2004). CT and AAC combined to:

- Rehabilitate 490 hectares of *andenes* and to put these back into production.
- Rehabilitate 24 km of canals using prehispanic technologies.
- Restore six ancient stone and clay-lined reservoirs.
- Restore one complete *amuna* in the district of Pampachiri, including the protection of the springs

and improvements to the pre-irrigation storage lake.
- Increase the capacity of over 10 lakes and reservoirs.
- Carry out full inventories of the agricultural terraces in the Chicha Soras and Sondondo valleys and of seven districts within the Nor Yauyos Cochas reserve.

All of this work was supported by archaeological excavations on the agricultural terraces, canals and reservoirs. Additionally, studies of past climate and environmental change were undertaken through the analysis of sediments and sub-fossil biological remains within wetlands (lakes and peat bogs) in both the Patacancha and Chicha Soras valleys (e.g., Chepstow-Lusty et al., 2003; Kemp et al., 2006; Branch et al., 2007). These studies provided key information on former land-use histories, and the environmental and human response to climate change, which complemented the archaeological and rural development work. Some of the key benefits of the work carried out by CT and AAC included:
- The use of locally available materials has meant that the communities are less reliant on outside help in order to maintain the infrastructure.
- Production on rehabilitated terraces is between 30% and 80% higher than on sloping fields at the same altitude.
- Approximately 20% of the water is required to irrigate terraced fields compared with sloping field systems.
- Soil erosion has been reduced massively.
- Improved lakes, the protection of springs and the recovery of *amunas* has meant that lakes have not dried up and that new springs have appeared within the valleys.

This work continues in the study area presented here with a project to rehabilitate a pre-Hispanic water dam, Ricococha Alta, located in the Rico tributary of the upper Chaclancayo Basin at 4450 m a.s.l. (Figure 3F). Working together with AAC, the Pamparomás authorities led by the Mayor Guillermo Palmadera and NGO's ECLOSIO and Junta de Desarrollo de Pamparomás, this new project aims to restore to working order a dam using a combination of modern technology and ancestral indigenous knowhow. This pilot project aims to address local water security issues through the re-use of existing abandoned but recoverable pre-Hispanic installed hydraulic structural capacity (Lane, 2019).

Clearly not all attempts to restore ancient agricultural systems will bring positive results, but there are some key approaches that may meet the challenges of climate change in the Ancash region, creating long-term benefits. These include:
- Identifying communities that retain at least partially the traditional social systems based upon a shared work ethic and where ideally the population still has a high percentage of young farmers present.
- Working in an area for a long continuous period and employing staff who are happy to live in the communities and who speak the local language.
- Listening to the local families and not imposing ideas upon them.
- Offering a very thorough training program before, during and after any intervention.
- Include follow up activities such as crop management and market training once the infrastructure has been rehabilitated.

Concluding Comments

The preliminary findings from the pilot research project 'Adaptive Capacity of Farming Communities to Climate Change in the Peruvian Andes (ACCESS)' have shown that there is considerable concern expressed by local communities in the Cordillera Blanca and Cordillera Negra (Ancash region) about the impact of climate change. These concerns include water shortages, increasing temperatures and glacier retreat, soil degradation, and greater problems with crop pests. These concerns appear to be exacerbated by a shortage of agricultural land, conflict between communities and a lack of state intervention. Drawing upon their knowledge, expertise and experience of working and living in these cordilleras, these communities have a great appreciation of the adaptive strategies required for a sustainable future, especially improved water management, economic diversification, greater community collaboration and state investment. Indeed, there is a clear willingness to embrace new ideas and to work in partnership with NGOs and universities, which is exemplified by the project to rehabilitate the pre-Hispanic water dam at Ricococha Alta in the CN. This piece of research-led rural development is being coordinated by several members of the ACCESS project team and draws upon previous archaeological surveys and the preliminary findings of both the ethnographic data and hydrological modelling. It demonstrates the considerable potential of restoring and utilising ancient water management infrastructure as part of an adaptive strategy to deal with the impact of climate change and reduced water availability. The hydrological modelling has also reinforced wider concerns about rising temperatures and increased variability in precipitation patterns, and the need to improve water management in both cordilleras to maintain effective levels of irrigation. This will help to reduce vulnerability (social, economic and environmental) and hopefully ensure a more sustainable future for farming and economic development. Our review of past climate change has demonstrated that variability of the South American Summer Monsoon (SASM) and the Intertropical Conversion Zone (ITCZ), as well as the El Niño Southern Oscillation (ENSO), has led to periods of significantly higher or lower precipitation in the past. The response of human communities in Ancash remains to be fully understood because of temporal uncertainties within archaeological data. Nevertheless, the abundance of well-preserved agricultural and water management infrastructure for specific cultural periods clearly indicates that human communities put a high demand on available water resources but also recognised the need for water conservation. The preliminary findings presented here have provided the basis for ongoing research in the CB and CN, as well as the regions of Ayacucho and Apurimac, which we hope will continue to improve our understanding of the adaptive capacity of farming communities to climate change in the Peruvian Andes: past, present and future.

Acknowledgements

We are grateful to the following communities and organisations for their assistance during the ACCESS pilot project: Unidos Venceremos village (CB), Pamparomás village (CN), Junta de Desarrollo Distrital de Pamparomás (CN), Universidad Nacional Santiago Antúnez de Mayolo (Huaraz), Ministerio de Cultura (Huaraz), ECLOSIO (University of Liège, Lima and Pamparomás) and Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM, Huaraz). Thank you to the British Academy for providing the funding for the research project (KF2\100158), and to the Academy of Medical Sciences for funding the initial networking programme (Food Production and Climate Resilience in Peru: Past, Present and Future (GCRFNG\100411)).

References

Aibar Ozejo, E. (1968). La visita de Guaraz en 1558. Cuadernos del Seminario de Historia. *Instituto Riva Agüero,* 9, 5-21.

Apaéstegui, J., Cruz, F. W., Sifeddine, A., Vuille, M., Espinoza, J. C., Guyot, J. L., Khodri, M., Strikis, N., Santos, R. V., Cheng, H., Edwards, L., Carvalho, E. and Santini, W. (2014). Hydroclimate variability of the northwestern Amazon Basin near the Andean foothills of Peru related to the South American Monsoon System during the last 1600 years. *Climate of the Past*, 10, 1967-1981.

Arkush, E. and Tung, T. A. (2013). Patterns of war in the Andes from the Archaic to the Late Horizon: Insights from settlement patterns and cranial trauma. *Journal of Archaeological Research* 21, 307–69.

Aste Cannock, N. (2018). *Evaluación de la demanda hídrica agrícola actual y futuros riesgos en la costa peruana mediante el caso del Proyecto Especial Chavimochic, La Libertad.* Pontificia Universidad Católica del Perú. Masters thesis.

Barrett, T., Feola, G., Krylova, V. and Khusnitdinova, M. (2017). The application of Rapid Appraisal of Agricultural Innovation Systems (RAAIS) to agricultural adaptation to climate change in Kazakhstan: A critical evaluation. *Agricultural Systems,* 151, 106-113.

Bird, B. W., Abbott, M. B., Vuille, M., Rodbell, D. T., Stansell, N.D. and Rosenmeier, M. F. (2011). A 2300-year-long annually resolved record of the South American summer monsoon from the Peruvian Andes. *Proceedings of the National Academy of Sciences,* 108, 8583–8588.

Branch, N. P., Kemp, R. A., Silva, B., Meddens, F. M., Williams, A., Kendall, A. and Pomacanchari, C. V. (2007). Testing the sustainability and sensitivity to climatic change of terrace agricultural systems in the Peruvian Andes: A pilot study. *Journal of Archaeological Science,* 34, 1-9.

Carey, M., French, A. and O'Brien, E. (2012). Unintended effects of technology on climate change adaptation: An historical analysis of water conflicts below Andean glaciers. *Journal of Historical Geography,* 38, 181–191.

Chepstow-Lusty, A., Frogley, M. R., Bauer, B. S., Bush, M. B. and Tupaychi Herrera, A. (2003). A late Holocene record of arid events from the Cuzco region, Peru. *Journal of Quaternary Science*, 18, 491-502.

Chepstow-Lusty, A. (2011). Agro-pastoralism and social change in the Cuzco heartland of Peru: A brief history using environmental proxies. *Antiquity,* 85, 570-82.

Cook, N. D. (1981). *Demographic collapse: Indian Peru,* 1520-1620. Cambridge, Cambridge University Press.

Cook, N. D. (1998). *Born to die: Disease and New World conquest, 1492-1650.* Cambridge, University of Cambridge Press.

Denevan, W. M. (2001). *Cultivated landscapes of native Amazonia and the Andes.* Oxford Geographical and Environmental Studies Series. Oxford, Oxford University Press.

Dillehay, T. D., Rossen, J. and Netherley, P. J. (1997). The Nanchoc tradition: The beginnings of Andean civilization. *American Scientist,* 85, 46–56.

Duputis, E. (2021). *Políticas de cambio climático en los Andes:* Diálogo entre escalas y saberes para la adaptación. Propuestas Andinas 18. Quito: Adaptación a las Alturas. Programa Bosques Andinos. CONDESAN.

Duviols, P. (1973). Huari y llacuaz: Agricultores y pastores. Un dualismo prehispánico de oposición y complementaridad. *Revista del Museo Nacional,* 39, 153-91.

Ferreira, F. (2012). *Back to the village? An ethnographic study of an Andean community in the early twenty-first century.* PhD thesis. Royal Holloway, University of London.

Garreaud, R. D., Vuille, M., Compagnucci, R. and Marengo, J. (2009). Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 281, 180–195.

Grimm, A. M. and Zilli, M. T. (2009). Interannual variability and seasonal evolution of summer monsoon rainfall in South America. *Journal of Climate,* 22, 2257–2275.

Haug, G. H., Hughen, K., Sigman, D. M., Peterson, L. C. and Röhl, U. (2001). Southward migration of the intertropical convergence zone through the Holocene. *Science,* 293, 1304–1308.

Herrera, A. (2017). Turismo patrimonial, identidad y desarrollo en el Perú. *Indiana,* 34, 199–231.

Herrera Wassilowsky, A. (2012). *La recuperación de tecnologías indígenas. Arqueología, tecnología y desarrollo en los Andes.* Estudios de la Sociedad Rural 41. Bogotá and Lima, Universidad de los Andes, Facultad de Ciencias Sociales, Departamento de Antropología; CLACSO; IEP; PUNKU, Centro de Investigación Andina.

Junta de Desarrollo Distrital de Pamparomás (2000). *Proyecto: Uso productivo del agua y desarrollo agroecológico de la microcuenca Chaclancayo*. Pamparomás, Peru, Junta de Desarrollo Distrital de Pamparomás.

Kanner, L. C., Burns, S. J., Cheng, H., Edwards, R. L. and Vuille, M. (2013). High-resolution variability of the South American summer monsoon over the last seven millennia: Insights from a speleothem record from the central Peruvian Andes. *Quaternary Science Reviews,* 75, 1–10.

Kemp, R. A., Branch, N. P., Silva, B., Meddens, F., Williams, A., Kendall, A. and Pomacanchari, C. V. (2006). Pedosedimentary, cultural and environmental significance of palaeosols within pre-Hispanic agricultural terraces in the southern Peruvian Andes. *Quaternary International,* 158, 13-22.

Kendall, A. (2004). Restauración de canales y andenes agrícolas prehispánicos en los Andes usando tecnología tradicional y apropiada. In Llerena, C. A., Inbar, M. and Benavides, M. A. (Eds.). *Conservación y abandono de andenes*. Lima, Universidad Agraria La Molina y Universidad de Haifa.

Kendall, A. (2005). Applied archaeology: Revitalizing indigenous agricultural technology within an Andean community. *Public Archaeology,* 4, 205-221.

Kendall, A. y Chepstow-Lusty, A., (2006). Cultural and environmental change in the Cuzco region of Peru: The rural development implications of combined archaeological and palaeoecological evidence. *In* Dransart, P. (Ed.). *Kay Pacha: Cultivating earth and water in the Andes*. British Archaeological Reports (BAR) S1478, 185-197.

Kendall, A. Aguirre-Morales M. and Aramburú, D. (2006). *Excavaciones en Andamarca*. Informe, Cusichaca Trust, Andahuaylas, Perú.

Kendall, A. and Rodríguez, A. (2009). *Desarrollo y perspectivas de los sistemas de andenería de los Andes centrales del Perú*. Cuzco, Institut Français d'Études Andines.

Kirkland, E. (2012). Indigenous knowledge and climate change adaptation in the Peruvian Andes. *Political Economy of the Environment in Latin America* (INTL1450), 1-37.

Kosok, P. (1965). *Life, land, and water in ancient Peru; An account of the discovery, exploration, and mapping of ancient pyramids, canals, roads, towns, walls, and fortresses of coastal Peru with observations of various aspects of Peruvian life, both ancient and modern*. New York, Long Island University Press.

Lane, K. (2006). *Engineering the puna: The hydraulics of agro-pastoral communities in a north-central Peruvian valley*. PhD thesis. Cambridge, University of Cambridge.

Lane, K. (2009). Engineered highlands: The social organisation of water in the ancient north-central Andes (AD 1000-1480). *World Archaeology,* 41, 169-90.

Lane, K. (2014). Water technology in the Andes. In Selin, H. (Ed.). *Encyclopaedia of the history of science, technology, and medicine in non-Western cultures,* 1–24. New York, Springer.

Lane, K. (2017). Water, silt and dams: Prehispanic geological storage in the Cordillera Negra, north-central Andes, Peru. *Revista de Glaciares y Ecosistemas de Montaña*, 2, 41–50.

Lane, K. (2019). High Altitude Andean Rehabilitation of Dams Project (HAARD), Cordillera Negra, central Andes, Peru. Gerda Henkel Humanitarian Aid and Social Welfare Projects - Accompanying Social Measures Initiative. Germany, Gerda Henkel Stiftung.

Levillier, R. (1926). *Gobernantes de Perú: Cartas y papeles siglo XVI: El Virrey Garcia de Hurtado de Mendoza, Marques de Cañete*. Vol. XIII: Segunda Parte (Documentos del Archivo de Indias). Madrid, Colección de Publicaciones Históricas de la Biblioteca de Congreso Argentino.

Llerena, C. A., Inbar, M. and Benavides, M. A. (Eds.) (2004). *Conservación y abandono de andenes*. Lima, Universidad Nacional Agraria La Molina, Universidad de Haifa.

Lynch, T. F. (1971). Preceramic transhumance in the Callejón de Huaylas. *American Antiquity*, 36, 139–48.

Mark, B. G. and McKenzie, J. M. (2007). Tracing increasing tropical Andean glacier melt with stable isotopes in water. *Environmental Science & Technology*, 41, 6955-60.

Maza, J. (2017). Introducción al estudio arqueológico del canal prehispánico Huiru Catac, cuenca alta de Nepeña: Tecnología hidráulica para integrar la puna, los valles interandinos y la costa. *Arkinka*, 265.

McKinney, D. C., Anderson, G. and Byers, A. (2011). *Adaptation to climate change: Case study – Glacial retreat and adaptation options in Peru's Río Santa basin (draft final).* United States Agency for International Development (USAID).

Obregón, G., Díaz, A., Rosas, G., Acuña, D., Avalos, G., Oria, C., Llacza, A. (2009). *Escenarios climáticos en la cuenca del río Santa para el año 2030 – Resumen técnico. Segunda comunicación nacional de cambio climático.* Lima, SENAMHI.

Olarte Navarro, B. (2007). La cuenca del río Chillón: Problemática y potencial productivo. *Ingeniería Industrial,* 25, 53-68.

Orlove, B. S. (2020). A minority of Peruvian mountain farmers benefit from government pandemic programs. *GlacierHub.*

Ortloff, C. R. (2010). *Water engineering in the ancient world: Archaeological and climate perspectives on societies of ancient South America, the Middle East, and South-East Asia*. Oxford, Oxford University Press.

Posthumus, H. and de Graaff, J. (2005). Cost-benefit analysis of bench terraces, a case study in Peru. *Land Degradation & Development,* 16, 1-11.

Posthumus, H. and Stroosnijder, L. (2010). To terrace or not: The short-term impact of bench terraces on soil properties and crop response in the Peruvian Andes. *Environment, Development and Sustainability,* 12, 263-276.

Pramova, E., di Gregorio, M. and Locatelli, B. (2015). I*ntegrating adaptation and mitigation in climate change and land-use policies in Peru*. Working paper 184, Bogor, Indonesia, CIFOR.

Raimondi, A. (1874). El Peru, *Tomo I, Parte Preliminar*. Lima: Imprenta del Estado.

Raymondi, A. M., Delgado-Arias, S. and Elder, R. C. (2012). Technological solutions for climate change adaptation in the Peruvian highlands. In Chhetri, N. (Ed.). *Human and social dimensions of climate change,* 3-30. Open Access: InTech.

Rasmussen, M. B. (2015). *Andean waterways: Resource politics in highland Peru.* Seattle and London, University of Washington State.

Rein, R., Lückge, A. and Sirocko, F. (2002). A major Holocene ENSO anomaly during the medieval period. *Geophysical Research Letters,* 31, L17211, 1-4.

Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A. and Dullo, W-D. (2005). El Niño variability off Peru during the last 20,000 years. *Paleoceanography,* 20, PA4003, 1-17.

Reuter, J., Stott, L., Khider, D., Sinha, A., Cheng, H., and Edwards, R. L. (2009). A new perspective on the hydroclimate variability in northern South America during the Little Ice Age. *Geophysical Research Letters,* 36, L21706, 1-5.

Sandweiss, D. H., Andrus, C. F. T., Kelley, A. R., Maasch, K. A., Reitz, E. J. and Roscoe, P. B. (2020). Archaeological climate proxies and the complexities of reconstructing Holocene El Niño in coastal Peru. *Proceedings of the National Academy of Sciences,* 117, 8271-8279.

Schoolmeester, T., Saravia, M., Andresen, M., Postigo, J., Valverde, A., Jurej, M., Alfthan, B. and Giada, S. (2016). *Outlook on climate change adaptation in the tropical Andes mountains. Mountain Adaptation Outlook Series.* Nairobi, Arendal, Vienna and Lima, United Nations Environmental Programme, GRID-Arendal and CONDESAN.

Schut, M., Klerkx, L., Rodenburg, J., Kayeke, J., Hinnou, L. C., Raboanarielina, C. M. and Bastiaans, L. (2015). RAAIS: Rapid Appraisal of Agricultural Innovation Systems (Part I). A diagnostic tool for integrated analysis of complex problems and innovation capacity. *Agricultural Systems,* 132: 1-11.

Seltzer, G., Rodbell, D. and Burns, S. (2000). Isotopic evidence for late Quaternary climatic change in tropical South America. *Geology,* 28, 35-38.

Skarbø, K. y Lambrou, J. (2015). Maize migration - Key crop expands to higher altitudes under climate change in the Andes. *Climate and Development,* 8(3), 245-255.

Smith, M. (1992). *CROPWAT, A computer program for irrigation planning and management.* FAO Irrigation and Drainage Paper 46. Rome, Food and Agriculture Organisation of the United Nations.

Stansell, N. D., Rodbell, D. T., Abbott, M. B. and Mark, B. G. (2013). Proglacial lake sediment records of Holocene climate change in the western cordillera of Peru. *Quaternary Science Reviews,* 70, 1-14.

Stansell, N. D., Licciardi, J. M., Rodbell, D. T. and Mark, B. G. (2017). Tropical ocean-atmospheric forcing of Late Glacial and Holocene glacier fluctuations in the Cordillera Blanca, Peru. *Geophysical Research Letters,* 44, 4176-4185.

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. (1995). Late Glacial Stage and Holocene tropical ice core records from Huascaran, Peru. *Science,* 269, 46-50.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Zagorodnov, V. S., Howat, I. M., Mikhalenko, V. N. and Lin, P.-N. (2013). Annually resolved ice core records of tropical climate variability over the past ~1800 years. *Science,* 340, 945-950.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E. and Porter, S. E. (2017). Ice core records of climate and environmental variability in the tropical Andes of Peru: Past, present and future. *Revista de Glaciares y Ecosistemas de Montaña,* 3, 25-40.

Torres, J., Frías, C. and de la Torre, C. (2014). *Adaptación al cambio climático en zonas de montaña.* Practical Action Consulting. Lima, Soluciones Prácticas.

Tremolada, P., Villa, S., Bazzarin, P., Bizzotto, E., Comolli, R. and Vighi, M. (2008). POPs in mountain soils from the Alps and Andes: Suggestions for a 'precipitation effect' on altitudinal gradients. *Water, Air, and Soil Pollution,* 188, 93–109.

USAID (United States Agency for International Development). (2011). *Peru climate change vulnerability and adaptation desktop study.* Written for USAID under the Climate Change Resilient Development Task Order, Washington, D.C., USAID.

Valdivia, C., Seth, A., Gilles, J. L., García, M., Jiménez, E., Cusicanqui, J. and Yucra, E. (2010). Adapting to climate change in Andean ecosystems: Landscapes, capitals, and perceptions shaping rural livelihood strategies and linking knowledge systems. *Annals of the Association of American Geographers,* 100, 818–834.

Vuille, M., Burns, S. J., Taylor, B. L., Cruz, F. W., Bird, B. W., Abbott, M. B., Kanner, L. C., Cheng, H. and Novello, V. F. (2012). A review of the South American monsoon history as recorded in stable isotopic proxies over the past two millennia. *Climate of the Past,* 8, 1309–1321.

Walshe, R. and Argumedo, A. (2016). Ayni, ayllu, yanatin and chanincha: The cultural values enabling adaptation to climate change in communities of the Potato Park, in the Peruvian Andes. *GAIA,* 25 (3), 166-173.

Willems, B., Leyva-Molina, W. M., Taboada-Hermoza, R., Bonnesoeur, V., Román, F., Ochoa-Tocachi, B. F., Buytaert, W. and Walsh, D. (2021). *Impactos de andenes y terrazas en el agua y los suelos: ¿qué sabemos?* Resumen de políticas, Proyecto "Infraestructura Natural para la Seguridad Hídrica". Lima, Forest Trends.