Climate change, deforestation patterns, freshwater availability and cultural shifts on prehistoric Easter Island (SE Pacific)

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Abstract

The remote and isolated Easter Island (Rapa Nui) has been the arena for classic debates on the potential consequences of human overexploitation of natural resources as a microcosmic model for the whole planet. Human-deterministic hypotheses have traditionally been preferred to proposals involving climate changes as drivers of socioecological shifts, especially in relation to the collapse of the ancient Rapanui civilization inhabiting the island before European contact (1722 CE). However, recent paleoecological studies have provided evidence for past climatic shifts, especially droughts, which have stimulated a paradigm shift from deterministic and exclusive views to a more holistic framework that considers both natural and anthropogenic factors as well as their feedbacks and synergies. This paper reviews the latest climatic, ecological and cultural reconstructions of precontact times and evaluates the potential impact of the different drivers on socioecological shifts. Especially noteworthy is the occurrence of some droughts in the last millennium that, coupled with human deforestation, severely affected the access of the prehistoric Rapanui civilization to freshwater but did not compromise the continuity of this ancient culture. Two main hypotheses have been proposed for how the Rapanui bypassed freshwater scarcity. According to the intraisland migration hypothesis, the latest drought recorded (1570-1720 CE) would have led to the abandonment of the former cultural center of the ancient Rapanui civilization (Lake Raraku) to move to Lake Kao, which became the new cultural core. This would have been linked to a profound cultural shift from the moai cult to the Birdman cult. In contrast, the coastal groundwater hypothesis proposes that coastal seeps were the main freshwater source during climatic droughts. These hypotheses are evaluated using the available archaeological and paleoecological evidence, and it is concluded that neither can be rejected; therefore, they could be complementary, rather than exclusive. The continuity of the Rapanui civilization in spite of landscape degradation is a good example of cultural resilience that challenges earlier deterministic explanations and emphasizes human adaptability to changing environments.

Keywords: Rapa Nui, prehistory, last millennium, Little Ice Age, drought, forest clearing, freshwater, brackish water, groundwater, intra-island migrations

Introduction

Easter Island (Rapa Nui) was first discovered by Europeans in 1722, when the Dutch expedition led by Jacob Roggeven landed there on Easter Sunday (April 5th). The Rapanui civilization that Europeans encountered on the island was not familiar with writing or metals; therefore, 1722 has been considered the end of their prehistory and the Neolithic culture on Easter Island. The prehistoric Rapanui civilization was of Polynesian origin –see Rull (2019) for a discussion on the discovery and initial settlement of the island- and is well known for its main worship subjects, the megalithic anthropomorphic statues called moais (Fig. 1). The ancient Rapanui have been considered responsible for the abrupt island-wide deforestation as a result of the overexploitation of natural resources that would have caused their own cultural collapse (Bahn & Flenley, 1992; Flenley & Bahn, 2003). This view has been called the ecocidal hypothesis and has been used as a microcosmic model for the whole planet (Diamond, 2005). Some believe that Polynesian rats could have participated in the forest clearing by consuming massive amounts of palm fruits, thus precluding forest regeneration (Hunt, 2007). The timing for island-wide deforestation varies according to the authors, ranging from approximately 800-1300 CE to 1400-1650 CE (Flenley & Bahn, 2003; Hunt & Lipo, 2011, and literature therein).

The ecocidal hypothesis dominated Easter Island research for decades, and many still consider this to be the paradigm for the disappearance of the ancient Rapanui civilization. However, other proposals have emerged more recently. The genocidal hypothesis proposes that the ancient Rapanui civilization remained healthy until European contact and that the cultural collapse was due to the postcontact introduction of alien epidemic diseases and slavery (Rainbird, 2002; Peiser, 2005; Hunt, 2007). A third possibility is a combination of both ecocidal and genocidal hypotheses (Brandt & Merico, 2015). It has also been speculated that the ancient Rapanui culture could have collapsed in barely four years, between 1770 and 1774, due to internal social conflicts (Fischer, 2005; Hunt & Lipo, 2011). All of these hypotheses consider human activities to be the main causes of ecological and cultural changes (human determinism). Other approaches highlight the potential action of climate changes, notably droughts, or the feedbacks and synergies between climatic and anthropogenic drivers (Rull, 2016b, 2018). However, the potential influence of these climate changes on socioecological developments has received little attention in comparison with human-deterministic approaches.

This paper summarizes the recent paleoecological evidence for climate changes that occurred during the last millennium and discusses how these environmental shifts could have affected ecological and cultural trends on the island prior to European contact. The discussion is focused on the potential influence of prehistoric climate shifts, deforestation patterns and changing freshwater availability, a critical feature for Easter Island's cultural developments that has not been seriously considered until recently (Rull, 2016b), on the ancient Rapanui civilization. The paper begins with a brief description of the present-day climate and hydrology of the island to highlight the critical nature of freshwater availability for both ecosystems and human life. Then, the prehistoric climatic, ecological and cultural conditions of precontact times are reviewed, with emphasis on the occurrence of extended (secular-scale) droughts and uneven deforestation patterns as potential drivers for severe landscape degradation and freshwater scarcity. The main hypotheses proposed to explain the continuity of the prehistoric Rapanui civilization in spite of such sustained environmental stress are presented and evaluated under a holistic perspective.

Present-day climate and freshwater sources

Easter Island is a small (167 km^2) and remote island situated in the southeastern Pacific, formed by the fusion of three volcanic cones: Kao, Poike and Terevaka (Fig. 2). The present-day climate on Easter Island is subtropical, with small seasonal temperature variations due to the influence of the ocean. The annual average temperature is 21 °C with a gentle seasonal range of 5 °C on average, between 18 °C in the Austral winter (July-September) and 23 °C in the Austral summer (January-March). Extreme temperatures vary between approximately 15 °C and 28 °C (Herrera & Custodio, 2008). The total annual rainfall ranges between 1100 and 1300 mm, with an average of 140 rainy days. The average seasonal variability ranges between minima of 70-80 mm/month (September-November) and maxima of 100-120 mm/month (April-June) (Azizi & Flenley, 2008; Mann et al., 2008). This seasonal variability is controlled by the interplay between three climate systems: the South Pacific Anticyclone (SPA), the South Pacific Convergence Zone (SPCZ) and the westerly storm tracks (Sáez et al., 2009). Potential evapotranspiration is approximately 850-950 mm/year; therefore, the climatic hydrological balance (precipitation/evapotranspiration ratio, or P/E) is above 1, which means that there is no water deficit during a typical year (Herrera & Custorio, 2008).

Interannual variability in precipitation is very high, ranging from 500 to >1800 mm/year (Azizi & Flenley, 2008). This variability is largely unpredictable, as it has not been possible to associate long-term precipitation changes with interannual periodic climatic oscillators such as the El Niño Sothern Oscillation (ENSO) (Genz & Hunt, 2003).

A recent survey using short-term observations (<2 years) identified a linear lapse rate in both temperature and precipitation values across the island, from coastal localities to the Terevaka highlands (Puleston et al., 2017). According to these estimates, temperatures were approximately 21 °C on coastal sites, with a decrease of -0.85 °C/100 m elevation (r^2 = 0.99), whereas precipitation increased at a rate of 175 mm/100 m elevation from coastal values of 1240 mm (r^2 = 0.87). Based on a detailed elevation model of the island and the predominant E-W direction of trade winds, the same study proposed the existence of a possible rain-shadow effect that disturbed the orographic precipitation pattern. This would affect the leeward sides of the main mountains, such as Poike and Terevaka (and, to a lesser extent, of the Kao crater), where total annual precipitation would be less than 850 mm/year. This value is in the range of the potential annual evapotranspiration values mentioned before; hence, these areas might be close to the boundary of the water deficit.

Despite the humid nature of Easter Island's climate, surface freshwater sources are scanty. Permanent surficial water currents and springs are absent due to the high permeability of the island's volcanic rocks and the existence of abundant fractures (Herrera & Custodio, 2008). After a rain event, surface water flows for only hours to a few days (Brosnan et al., 2018). The only stable freshwater bodies are two lakes (Kao and Raraku) and a marsh (Aroi) located within volcanic craters, a combination locally known as rano (Fig. 3). There is also a groundwater system where freshwater accumulates on top and salinity increases with depth due to the penetration of seawater from below, which creates a density gradient (Herrera & Custodio, 2008) (Fig. 4). This groundwater system is shallower along the coasts, where natural brackish seeps may occur (Brosnan et al., 2018). Therefore, freshwater is more accessible in coastal environments, where wells for human use are common today. Rano Aroi, situated at ~430 m elevation, is an exception, and its marsh is thought to be fed by groundwater penetrating the volcanic core. Lakes Kao and Raraku are fed solely by precipitation and are hydrologically disconnected from the groundwater system (Herrera and Custodio, 2008).

This hydrological system was likely essentially the same in prehistory, although the water content, distribution and physico-chemical properties (e.g., salinity) could have changed due to climate shifts affecting the climatic hydrological balance (P/E). It has also been suggested that orographic climatic gradients have existed in the past (Azizi & Flenley, 2008), although their rates may not have necessarily been the same. The next section summarizes the existing evidence for climatic and ecological changes during Easter Island's prehistory based on recently published (from the last decade) paleoecological records.

Prehistoric conditions

Paleoecological studies of Aroi, Kao and Raraku sediments have provided most of the evidence for past climatic changes and deforestation patterns on Easter Island. The first palynological studies were used to support the ecocidal hypothesis (Flenley & King, 1984; Flenley et al., 1991). Claims for a role of climate shifts in deforestation (e.g., Hunter-Anderson, 1998; McCall, 1993; Nunn, 2000) were dismissed because of the lack of paleoecological evidence (Flenley & Bahn, 2003). Further multiproxy paleoecological analysis of new cores retrieved from the same sites suggested that climatic changes, notably droughts, could have had a role in island deforestation (Mann et al., 2008; Sáez et al., 2009). However, none of these studies was able to provide a continuous and chronologically coherent record of the last millennia due to an extended sedimentary gap encompassing several millennia and the occurrence of frequent radiocarbon age inversions, which prevented the development of reliable age-depth models (Rull et al., 2013).

Further coring provided records containing information for the last millennia, but the problem of age inversions remained (Horrocks et al., 2012a, b, 2013, 2015). A continuous and chronologically coherent sediment record of the last millennium was obtained in the Kao sediments (Gossen, 2007), but paleoclimatic and paleoecological information is still unavailable. See Rull (2016a) for a thorough database of sediment cores retrieved to date on Easter Island and all radiocarbon ages measured in them. Recently, it has been possible to obtain continuous and chronologically coherent records from Raraku, Aroi and Kao that provide paleoclimatic and paleoecological information for the last three millennia (Cañellas-Boltà et al., 2013; Rull et al., 2015, 2016, 2018). The main results obtained from these records are summarized in the following subsections, with an emphasis on climate shifts, especially in reference to the hydrological balance, and spatiotemporal deforestation patterns.

Climatic changes

Multiproxy analyses (sedimentology, mineralogy, organic and inorganic geochemistry, pollen, diatoms) of the Raraku sediments provided evidence for the occurrence of two phases of arid climates leading to the lake drying out (Fig. 5). The first of these droughts took place between 500 CE and 1200 CE during the Medieval Climatic Anomaly (MCA), when warm and dry conditions prevailed in the South Pacific basin (Nunn & Britton, 2001; Nunn, 2007). The time interval proposed by different authors for the Polynesian settlement of the island (800-1200 CE) falls within this arid phase (Rull, 2019). The second drought occurred between 1570 CE and 1720 CE, during the Little Ice Age (LIA) and just before European contact (Cañellas-Boltà et al., 2013), and was associated with the occurrence of several drought phases in the Pacific basin during the same period (Nunn, 2000, 2007). Between these two arid phases, a humid period extended from 1200 CE and 1570 CE, coinciding with the maximum development of the Rapanui civilization and the so-called "1300 event", a phase of assumed cool and wet Pacific climates (Nunn, 2007).

Similar analyses carried out in the Aroi sediments also documented some century-scale dry climatic phases, the first between approximately 300 BCE and 50 CE, the second between 600 CE and 1100 CE, roughly coinciding with the MCA drought recorded at Raraku and a third phase that could not be attributed to either climatic drought or anthropogenic influence, or to both (Rull et al., 2015). During the LIA Raraku drought (1570-1720 CE), the Aroi record shows an abrupt deforestation event, between 1520 CE and 1620 CE (Fig. 5). The Kao record encompasses the last millennium (ca. 900 CE to 1800 CE), and although the main vegetation trends have already been disclosed (see below), independent paleoclimatic inferences based on biomarker analysis are still in progress (Rull et al., 2018).

Deforestation patterns

The former idea of an abrupt, island-wide deforestation event occurring between 800-1300 and 1400-1650 CE (Flenley & Bahn, 2003; Mann et al., 2008; Mieth & Bork, 2010) has been considered an artifact due to the occurrence of the previously mentioned millennial-scale sediment gap in the first paleoecological records (Rull et al., 2013). The recently obtained continuous and chronologically coherent pollen records from Aroi, Kao and Raraku provide a different view, as they show that different sites were deforested at different times and at different rates (Cañellas-Boltà et al., 2013; Rull et al., 2015, 2018).

In the Raraku basin, forest clearing was initiated very early and lasted approximately 2000 years (Cañellas-Boltà et al., 2013). This vegetation change proceeded with three main pulses. The initial step consisted of a minor forest retraction (450 BCE) followed by a stabilization until the last millennium, when two major pulses occurred (Fig. 5). The more intense phase started in 1200 CE and led to a landscape dominated by grasslands but with palm-forest stands still present. This occurred at the end of the MCA drought and coincided with an increase in fire incidence, suggesting that both climate and humans (and their corresponding synergies) could have had a role in this deforestation acceleration. The final deforestation pulse, leading to a landscape totally dominated by grasslands, occurred by 1450 CE, during the maximum development of the ancient Rapanui culture. The lack of evidence for climatic shifts and a further fire exacerbation suggests that humans were the main drivers of the final forest clearing.

In Aroi, grasslands and forests coexisted during the last three millennia, although grasslands dominated the landscape until about 1400 CE, when a relatively rapid forest expansion led to a mostly forested landscape (Rull et al., 2015). Maximum forest cover was attained by 1500 CE, when a sudden deforestation event began that removed the forests in approximately one century (Fig. 5). This coincided with the Raraku LIA drought and a significant increase in fires, suggesting that both climate and humans could have been active deforestation agents. Paleoecological analyses of the Kao record are still in progress, but preliminary data show an initial forest clearing at approximately 1050 CE, likely related to the MCA Raraku drought, because of the absence of fire indications (Seco, 2018). Total deforestation started by 1350 CE, coinciding with a gentle increase in fires, and was completed by 1600 CE, coinciding with a major charcoal increase coeval with the LIA Raraku drought (Fig. 5). Once more, climate-human synergies seem to have been in play. This time, however, humans seem to have had more influence, as suggested by the coeval sudden increase in coprophilous fungi spores, commonly used as indicators of domestic herbivores and, hence, of human presence (Van Geel et al., 2003).

Past freshwater availability

Knowledge of prehistoric climatic changes and deforestation patterns is used here to discuss how changes in freshwater availability and forest distribution could have affected cultural developments. The abovementioned limitations imposed by Easter Island's hydrological system make freshwater availability especially critical for human life. In addition, contrary to other Polynesian societies (Nunn, 2007), the ancient Rapanui culture did not use irrigation practices for cultivation (Puleston et al., 2017; Hunt & Lipo, 2011). In these conditions, freshwater availability for agriculture and other human uses was heavily dependent on rain, a highly unpredictable resource on the island (see above), or the proximity to a lake. Therefore, it could be expected that droughts such as those reported here severely affected the prehistoric Rapanui civilization, especially in terms of freshwater availability. However, recent archaeological studies with an emphasis on cultivation practices showed that this civilization remained healthy until European contact (Mulrooney, 2013; Stevenson et al., 2015). Two main hypotheses, the intraisland migration hypothesis and the coastal groundwater hypothesis, have been proposed to explain how the Rapanui civilization circumvented freshwater scarcity, thus guaranteeing the continuity of the Rapanui civilization in spite of environmental degradation.

Intraisland migrations

At the time of its maximum development, the cultural center of the Rapanui culture, represented by the moai cult, was the Raraku crater, the quarry where the moai were carved, containing a small shallow lake (~300 m diameter and ~2 m deep). The moai were carved on the soft volcanic tuff that forms the Raraku crater using stone tools (toki) made of harder basalt rocks obtained from other craters (Gioncada et al., 2010). After carving, the moai were transported by means that are still debated to every part of the island and placed into groups on rectangular stone platforms (ahu). The entire Rapanui civilization was organized around the moai cult, during which more than 950 moai and 300 ahu were built and placed all over the island (Fig. 2). The moai cult ceased at some point and was replaced by the Birdman cult, involving a totally different religious, political and social organization (Robisnon & Stevenson, 2017). The Birdman cult was centered on the ceremonial village of Orongo, situated on top of the Kao crater, whose lake is, by far, the largest and deepest on the island (>1 km diameter and >10 m depth). The timing of the shift from the moai cult to the Birdman cult is uncertain, ranging from the mid-16th to the late 18th centuries. A number of possible explanations exist for this cultural shift, most of them founded on human determinism, but the available evidence is not conclusive (review in Rull, 2016b). Recently, an alternative explanation has been proposed that considers both natural and human drivers of ecological change, as well as their corresponding feedbacks and synergies (Rull, 2018).

According to the above paleoecological evidence, the Raraku crater and its surroundings were deforested by 1450 CE and dried out roughly a century later, during the LIA, remaining devoid of water for a century and a half (Cañellas-Boltà et al., 2013). The last signs of cultivation date from 1300-1450 CE (Fig. 5) (Horrocks et al., 2012a). This suggests that the site turned into a wasteland unable to support the flourishing Rapanui society, which would have abandoned Raraku in the search for other freshwater sources (Rull, 2016b). Likely due to its large size and depth, Lake Kao did not dry out during the last millennia (Rull, 2016a), and hence, it was better for supporting human life. The Kao catchment may have been already settled by humans, as suggested by its earlier deforestation (1350 CE) coeval with an increase in fires. However, the absence of fire during the next two centuries suggests that the catchment was not settled permanently until 1600 CE, as indicated by the sudden and maintained fire incidence and the permanent presence of domestic herbivores (Seco, 2018). This coincides with archaeological evidence indicating that the ceremonial village of Orongo, the center of the Birdman cult, was founded by 1600 CE (Robinson & Stevenson, 2017). In this scenario, the end of the moai industry could be explained, in part, by the different rock composition of the Raraku and the Kao craters. In the Raraku quarry, the moai were carved on tuff using tools made from harder rocks, mostly basalt, obtained in other craters, the Kao among them. The Kao crater is made of basalt and, therefore, much more difficult to carve with the technology available to the Neolithic Rapanui society (Gioncada et al., 2010).

The highland Aroi marsh was also a potential destination for the ancient Rapanui escaping from the inhospitable Raraku catchment during the LIA drought. It is possible that, owing to the elevational precipitation gradient, drought was less intense in the highlands, and this marsh contained freshwater. Human presence during the LIA drought is supported by the occurrence of deforestation by fire between about 1550 CE and 1650 CE (Rull et al., 2015). However, the site was likely abandoned by 1700 CE, as indicated by the abrupt fire decrease, and the last evidence of cultivation dated to 1670 CE (Fig. 5) (Horrrocks et al., 2015). The decrease in Aroi fires was followed by a rapid fire increase on Raraku, suggesting that Rapanui people could have been able to return to Raraku, whose internal lake was replenished with freshwater during the humid phase following the LIA (Cañellas-Boltà et al., 2015). The occurrence of precontact intraisland migrations is supported by archaeological evidence of shifting land use starting in 1600 CE (Stevenson et al., 2015). According to this evidence, reductions in land-use intensity would have been more intense on drier and less fertile sectors, which increased land use pressure on other parts of the island. Intraisland migrations, usually from coastal to inland sites, seem to have been common on other Pacific islands during the LIA (Nunn, 2007). It is also possible that the desiccation of Lake Raraku could have caused changes in the sociopolitical dominance of the westernmost Rapanui clans, coupled or not with intraisland migrations (Rull, 2016b).

Coastal waters

A different view has been proposed recently by Brosnan et al. (2018), who concluded that brackish coastal seeps could have been the main source of water for the ancient Rapanui civilization to survive on during the LIA drought. Such a conclusion is based on the consideration that other potential freshwater sources (permanent lakes, marshes, ephemeral streams and pools, taheta), although utilized by the prehistoric Rapanui, would not have been sufficient to support a population of thousands of individuals. According to these authors, Lake Kao is too difficult to access to have been a routine source of freshwater, and moreover, there is no evidence of human habitation on its shores. Lake Raraku is considered to be a reliable source of freshwater but only for the surrounding populations. The same would be true for Rano Aroi, which is unlikely to have been used to satisfy the needs of the whole island due to its remoteness. Temporary water currents and ponds were also considered too ephemeral for such purposes, and taheta were too small and too susceptible to water evaporation for large-scale human use (Brosnan et al., 2018). This, together with the absence in the archaeological record of large water containers and intense habitation near lakes and marshes, led these authors to conclude that coastal seeps would have been crucial for prehistoric Rapanui subsistence.

All waters found today in coastal seeps are brackish (ca. 4 to 28 g/L, compared to 1 g/L or less for freshwater and 35 g/L of seawater), which led Brosnan et al. (2018) to suggest that the Rapanui drank brackish water, a fact that, according to these authors, has been well documented historically. The Rapanui did not have the technology to drill deep wells on volcanic rocks; to capture fresh and brackish waters from coastal seeps, they used pits excavated parallel to the shoreline. Remains of these structures, called puna, have been found on several sites along the island's coast, which were the preferred sites for the Rapanui to live. Therefore, fresh/brackish water sources would have been frequent, widespread and close to populated sites (Brosnan et al., 2018). According to DiNapoli et al. (2019), the ahu, in addition to their ritual meaning, would have a signaling function to indicate the situation of such coastal seeps.

A holistic view

Easter Island has been used as an example of the advantages of considering a holistic perspective including environmental and anthropogenic forcings and their corresponding feedbacks and synergies rather than relying on debates based on environmental- vs. human-deterministic approaches (Rull, 2018). The case of freshwater availability can also be addressed from such a perspective. The advantages and drawbacks of intraisland migrations and the use of coastal seeps to ensure a permanent freshwater supply have recently been discussed, and it has been concluded that these strategies would have coexisted and, hence, they are complementary, rather than exclusive (Rull, in press).

The intraisland migration hypothesis is well supported by recent archaeological and paleoecological evidence. The main drawbacks for Lake Kao to have been a routine freshwater source during the LIA drought are the difficulty of access and the lack of archaeological evidence of habitation at lake margins (Brosnan et al., 2018). It is true that the inner Kao walls are high and steep, but they are not impracticable at all, as it is possible to easily descend to the lake and come back by foot in approximately one hour or less (Fig. 3). Modern paleoecologists know this well, and we have done the same in sediment-coring campaigns with all the equipment and the necessary provisions. The ancient Rapanui demonstrated an outstanding transport capacity by transporting the *moai* (up to 20 m high and over 250 tons of weight) from the Raraku quarry to any part of the island, including elevations above 200 m (Fig. 2). Transporting water across the Kao walls is a much easier task that could be performed on a daily basis.

On the other hand, human presence around the lake is well documented by the relict village of Orongo, which was the center of the Rapanui culture during the LIA drought since at least 1600 CE. Archaeological evidence of this fact is abundant and well preserved, including almost-intact stone dwellings and many petroglyphs featuring the Birdman cult and other representations (Figs. 6 and 7). The inhabitants of Orongo could have easily obtained freshwater from Lake Kao as explained above. Indeed, the Birdman cult required members descend to the sea and return to Orongo by the outer Kao cliffs, which were much higher and more difficult to climb than the inner walls of this crater (Fig. 6). This, together with a one-km swim to the Motu Nui islet (Fig. 2) to obtain the eggs of the migratory sooty tern and come back, was performed on the same day by the Rapanui athletes. Obtaining freshwater from the lake is a much easier task that could be performed by common people, such as paleoecologists, as a routine. It seems totally unreasonable that Orongo people would refuse to routinely obtain water from Lake Kao to avoid a barely one-hour trip to the lakeshore.

In addition, there is sound paleoecological evidence of intense precontact agriculture along the Kao shores, where large-scale deforestation by fire and mixed-crop production (paper mulberry, taro, banana, greater yam) on gardened terraces has been documented (Horrocks et al., 2012b, 2013). Most of this evidence of cultivation has been found on the lakeshores immediately below Orongo, which suggests a connection with this relict village (Fig. 6). There is no evidence of human dwellings on lakeshores, and it is reasonable to assume that the agricultural products were transported to Orongo for human consumption and, eventually, distribution to other places. The same would be true for fresh lake water, whose transport could have been performed in the same way and at the same time. Transporting agriculture products but not freshwater from the Lake Kao shores to Orongo seems absurd. Given the already mentioned outstanding transport capacity of the Rapanui people, distributing agricultural products and water from Orongo to other places would have been very easy.

The main advantage of the coastal groundwater hypothesis is that water sources are numerous, widespread and closer to the habitation sites, but there are two main drawbacks to considering this to be the only possibility of obtaining freshwater during the LIA drought. First, this hypothesis has been proposed after the detailed study of only the eastern half of the island, where access is easier. With the present state of knowledge, this situation cannot be extrapolated to the western sector, which included the center of the Rapanui culture during the LIA drought, where physiography is very different and coastal seeps have not been reported. Second, all present-day coastal seeps identified in the eastern sector produce brackish water, rather than freshwater (Brosnan et al., 2018). If this was the main water source for the ancient Rapanui during the LIA drought, they must have survived for about six generations (150 years; 1570-1720 CE) with only brackish water for drinking and for agriculture, which is challenging and does not seem to be the most efficient solution. Finally, as rain is the only freshwater source for the groundwater system, such a supply would have been drastically reduced during a drought, as discussed here, suggesting that the salinity of coastal seeps could have been higher than today. Therefore, coastal seeps could have been used by the ancient Rapanui, but other truly freshwater sources would have been needed to maintain this civilization in good shape.

In summary, both the intraisland migration and coastal groundwater hypotheses have advantages and drawbacks, but with the available evidence, neither of them can be rejected. Therefore, there is no reason to exclude any of these hypotheses to explain freshwater availability during climatic droughts. From a human perspective, it seems reasonable to take advantage of any freshwater sources available, rather than being selective, in times of scarcity.

Conclusions

During prehistoric times, Easter Island experienced at least two extended droughts, the first (500-1200 CE) during the Medieval Climate Anomaly (MCA) and the second (1570-1720 CE) during the Little Ice Age (LIA), separated by a humid phase, which coincided with the maximum development of the Rapanui civilization. Rather than being abrupt and island-wide, deforestation was gradual and heterogeneous at both spatial and temporal scales; different sites were deforested at different times and at different rates. The coupled action of climatic (drought) and anthropogenic (deforestation) drivers severely affected the access of the prehistoric Rapanui civilization to freshwater, but this did not compromise the continuity of this ancient culture, which remained healthy until European contact. Two main strategies have been proposed for how the Rapanui civilization circumvented freshwater scarcity. The intraisland migration hypothesis proposes that drought would have caused the abandonment of Lake Raraku and its surroundings and the migration to Lake Kao catchment, linked to the cultural revolution represented by the shift from the moai cult to the Birdman cult. In contrast, the coastal groundwater hypothesis contends that brackish coastal seeps were the main freshwater source. The evaluation of these hypotheses using the available archaeological and paleoecological evidence shows that none can be rejected and that both Lake Kao and coastal seeps could have been used by the ancient Rapanui civilization to circumvent climatic stress. Regardless of the strategy adopted, the continuity of the Rapanui culture in spite of landscape degradation by anthropogenic deforestation and climatic drought is a good example of cultural resilience that challenges former deterministic explanations and emphasizes human adaptability to changing environments. It is hoped that further research will provide new empirical data not only to test the existing hypotheses but also to propose new ones, thus providing a clearer picture of how ancient Easter Islanders circumvented the scarcity of freshwater to keep living on the island and developing their civilization.

References

Azizi, G., Flenley, J.R. 2008. The last glacial maximum climatic conditions on Easter Island. Quaternary International 184, 166–176.

Bahn, P., Flenley, J. 1992. Easter Island, Earth Island. Tames & Hudson, London.

Brandt, G., Merico, A. 2015. The slow demise of Easter Island: insights from a modelling investigation. Frontiers in Ecology and Evolution 3, 13, doi: 10.3389/fevo.2015.00013.

Brosnan, T., Becker, M.W., Lipo, C.P. 2018. Coastal groundwater discharge and the ancient inhabitants of Rapa Nui (Easter Island), Chile. Hydrogeology Journal 27, 519-534.

Cañellas-Boltà, N., Rull, V., Sáez, A., Margalef, O., Bao, R., Pla-Rabes, S., Blaauw, M., Valero-Garcés, B. & Giralt, S. 2013. Vegetation changes and human settlement of Easter Island during the last millennia: a multiproxy study of Lake Raraku sediments. Quaternary Science Reviews 72, 36-48.

Diamond, J. 2005. Collapse. How societies choose to fail or survive. Allen Lane, London.

DiNapoli, R.J., Lipo, C.P., Brosnan, T., Hunt, T.L., Hixon, S., Morrison, A.E., Becker, M. 2019. Rapa Nui (Easter Island) monument (ahu) locations explained by freshwater sources. PLOS ONE 14, doi: 10.137/journal. Pone.02010409.

Fischer, S.R. 2005. Island at the End of the World. The Turbulent History of Easter Island. Reaction Books, London.

Flenley, J.R., Bahn, P.G. 2003. The enigmas of Easter Island. Oxford University Press, Oxford.

Flenley, J.R., King, S. 1984. Late Quaternary pollen records from Easter Island. Nature 307, 47–50.

Flenley, J.R., King, A.S.M., Jackson, J., Chew, C. 1991. The Late Quaternary vegetational and climatic history of Easter Island. Journal of Quaternary Science 6, 85–115.

Genz, J., Hunt, T.L. 2003. El Niño/southern oscillations and Rapa Nui prehistory. Rapa Nui Journal 17, 7–14.

Gioncada, A., González-Ferran, O., Lezzerini, M., Mazzuoli, R., Bisson, M., Rapu, S.A. 2010. The volcanic rocks of Easter Island (Chile) and their use for the moai sculptures. European Journal of Mineralogy 22, 855-867.
Gossen, C. 2007. Report: the mystery lies in the *Scirpus*. Rapa Nui Journal 21, 105-110.
Herrera, C., Custodio, E. 2008. Conceptual hydrogeological mode l of volcanic Easter Island (Chile) after chemical and isotopic surveys. Hydrogeology Journal 16, 1329–1348.
Horrocks, M., Baisden, W.T., Flenley, J., Feek, D., González-Nualart, L., Haoa- Cardinali, S., Edmunds Gorman, T. 2012a. Fossil plant remains at Rano Raraku, Easter Island's statue quarry: evidence for past elevated lake level and ancient Polynesian agriculture. Journal of Paleolimnology 46, 767–783.
Horrocks, M., Baisden, W.T., Nieuwoudt, W. T., Flenley, J., Feek, D., González-Nualart, L., Haoa-Cardinali, S., Edmunds Gorman, T. 2012b. Microfossils of Polynesian cultigen sin lake sediment cores from Rano Kau, Easter Island. Journal of Paleolimnology 47, 185–204.
Horrocks, M., Marra, M., Baisden, W.T., Flenley, J., Feek, D., González-Nualart, L., Haoa-Cardinali, S., Edmunds Gorman, T. 2013. Pollen, phytoliths, arthropods and high-resolution 14C sampling from Rano Kau, Easter Island: evidence for late quaternary environments, ant (formicidae) distributions and human activity. Journal of Paleolimnology 50, 417–432.
Horrocks, M., Baisden, W. T., Harper, M. A., Marra, M., Flenley, J., Feek, D., Haoa-cardinali, S., Keller, E.D., González Nualart, L., Edmunds Gorman, T. 2015. A plant microfossil record of late quaternary environments and human activity from Rano Aroi and surroundings, Easter Island. Journal of Paleolimnology 54, 279–303.
Hunt, T.L. 2007. Rethinking Easter Island's ecological catastrophe. Journal of Archaeological Science 34, 485-502.
Hunt, T.L., Lipo, C. 2011. The Statues that Walked. Free Press, NewYork.
Hunter-Anderson, R.L. 1998. Human vs. climatic impacts at Rapa Nui, Did people really cut down all those trees? Easter Island in Pacific context, South Seas Symposium: In: Stevenson, C.M., Lee, G., Morin, F.J. (Eds.), Proceedings of the Fourth International Conference on Easter Island and East Polynesia, Alburquerque, USA, pp. 95–99.
Mann, D., Edwards, J., Chase, J., Beck, W., Reanier, R., Mass, M., Finney, B., Loret, J. 2008. Drought, vegetation change, and human history on Rapa Nui (Isla de Pascua, Easter Island). Quaternary Research 69, 16–28.
McCall, G. 1993. Little Ice Age, some speculations for Rapanui. Rapa Nui Journal 7, 65–70.
Mieth, A., Bork, H. 2010. Humans, climate or introduced rats -which is to blame for the woodland destruction on prehistoric Rapa Nui (Easter Island)? Journal of Archaeological Science 37, 417-426.
Mulrooney, M. 2013. An island-wide assessment of the chronology of settlement and land use on RapaNui (Easter Island) based on radiocarbon data. Journal of Archaeological Science 40, 4377-4399.
Nunn, P.D. 2000. Environmental catastrophe in the Pacific Islands around A.D. 1300. Geoarchaeology 15, 715-740.
Nunn, P.D. 2007. Climate, Environment and Society in the Pacific during the Last Millennium. Elsevier, Amsterdam.
Nunn, P.D., Britton, J.M.R. 2001. Human-environment relationships in the Pacific, Islands around A.D. 1300. Environment and History 7, 3-22.
Peiser, B. 2005. From genocide to ecocide, the rape of Rapa Nui. Energy and Environment 16, 513-539.
Puleston, C.O., Ladefoged, T.N., Haoa, S., Chadwick, O.A., Vitousek, P.M., Stevenson, C.M. 2017. Rain, sun, soil, and sweat: a consideration of population limits on Rapa Nui (Easter Island) beofre European contact. Frontiers in Ecology and Evolution 5, 69, doi:103389/fevo.2017.00069.
Rainbird, P. 2002. A message for our future? The Rapa Nui (Easter Island) ecodisaster and Pacific environments. World Achaeology 33, 436-451.

Robinson, T., Stevenson, C. M. 2017. The cult of the Birdman: religious change at 'Orongo, Rapa Nui (Easter Island). Journal of Pacific Archaeology 8, 88–102.
Rull, V. 2016a. The EIRA database: Last Glacial and Holocene radiocarbon ages from Easter Island's sedimentary records. Frontiers in Ecology and Evolution 4, 44, doi: 10.3389/fevo. 2016.00044.
Rull, V. 2016b. Natural and anthropogenic drivers of cultural change at Easter Iisland: review and new insights. Quaternary Science Reviews 150, 31-41.
Rull, V. 2018. Strong fuzzy EHLFS: a general conceptual framework to address past records of environmental, ecological and cultural change. Quaternary 1, 10, doi:103390/quat1020010.
Rull, V. 2019. Human discovery and settlement of the remote Easter Island (SE Pacific). Quaternary 2, 15, doi:103390/quat2020015.
Rull, V., Cañellas-Boltà, N., Sáez, A., Margalef, O., Bao, R., Pla-Rabes, S., Valero-Garcés, B., Giralt, S. 2013. Challenging Easter Island's collapse: the need for interdisciplinary synergies. Frontiers in Ecology and Evolution 2, 56, doi: 10.3389/fevo.2014.00056.
Rull, V., Cañellas-Boltà, N., Margalef, O., Sáez, A., Pla-Rabes, S., Giralt, S. 2015. Late Holocene vegetation dynamics and deforestation in Rano Aroi: implications for Easter Island's ecological and cultural history. Quaternary Science Reviews 126, 219-226.
Rull, V., Cañellas-Boltà, N., Margalef, O., Pla-Rabes, S., Sáez, A., Giralt, S. 2016. Three millennia of climatic, ecological and cultural change on Easter Island: an integrative overview. Frontiers in Ecology and Evolution 4, 29, doi: 10.3389/fevo.2016.00029.
Rull, V., Montoya, E., Seco, I., Cañellas-Boltà, N., Giralt, S., Margalef, O., Pla-Rabes, S., D'Andrea, W., Bradley, R., Sáez, A. 2018. CLAFS, a holistic climatic-ecological anthropogenic hypothesis on Easter Island's deforestation and cultural change: proposals and testing prospects. Frontiers in Ecology and Evolution 6, 32, doi:103389/fevo.2018.00032.
Sáez, A., Valero-Garcés, B., Giralt, S.,Moreno, A., Bao, R., Pueyo, J.J., Hernández, A., Casas, D. 2009. Glacial to Holocene climate changes in the SE Pacific. The Raraku Lake sedimentary record (Easter Island, 27°S). Quaternary Science Reviews 28, 2743–2759.
Seco, I. 2018. Historia ecológica de la Isla de Pascua: análisis palinológico del último milenio en Rano Kao (Ecological history of Easter Island: palynological analysis of the last millennium in Rano Kao). MS dissertation, University of Barcelona.
Stevenson, C.M, Puleston, C.O., Vitousek, P.M., Chadwick, O.A., Haoa, S., Ladefoged, T.N. 2015. Variation in Rapa Nui (Easter Island) land use indicates producyion and population peaks prior to European contact. Proceedings of the National Academy of Sciences USA 112, 1025-1030.
Van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., Hakbijl, T. 2003. Environmetal reconstruction of a Roman Period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. Journal of Archaeological Science 30, 873-883.
Van Tilburg, J. A. 1994. Easter Island: Archaeology, Ecology, and Culture. Smithsonian Institution Press, Washington.

Figure captions

1. Ahu Tongariki, one of the most representative moai complexes, with the cliffs of the Poike volcano in the background (see Fig. 2 for location). The moai of this ahu are up to 9 m high and 90 tons in weight. Photo: V. Rull.
2. Topographic sketch map of Easter Island and the sites mentioned in the text. The position of the island on the world map is indicated by a red star. Permanent lakes and marshes are in blue. The location of Orongo (Og) and the Motu Nui islet (MN) are highlighted by red dots. Green dots represent the distribution of present-day *moai* and *ahu*, according to Van Tilburg (1994). Red lines indicate the westernmost boundary of studies by Brosnan et al. (2018) and DiNapoli et al. (2019) regarding coastal groundwater seeps.
3. The three permanent water bodies of Easter Island. A) The Aroi marsh (~150 m diameter) situated on the Terevaka highlands at ~430 m elevation (Fig. 2). B) Lake Kao (~1.25 km diameter and >10 m depth), situated on the westernmost part of the island, at approximately 110 m elevation (Fig. 2). The surface of the lake is a mosaic of deep waters and floating-mat patches of approximately 3 m depth, which can be walked across. The photo was taken from the upper part of a pathway used today to descend from the crest of the Kao crater to the lakeshore. C) Lake Raraku (~300 m diameter and ~2 m depth), situated on the eastern part of the island (Fig. 2). Photos: V. Rull.
4. Schematic cross-section of a N-S transect showing the hydrological model of Easter Island. Note the progressive thinning of the freshwater table toward the coast. The approximate elevation of lakes Kao and Raraku and the position of the Aroi marsh are indicated. Redrawn from Herrera & Custodio (2008).
5. Summary of climatic and vegetation shifts recorded in continuous and chronologically coherent sediment cores from Aroi (Rull et al., 2015), Kao (Seco, 2018) and Raraku (Cañellas-Boltà et al., 2013) sediments using multiproxy paleoecological analyses. Climatic phases according to Nunn (2007). Gray bands represent the droughts recorded at Raraku, during which the lake dried out. Abbreviations: ch – charcoal, as a proxy for fires, cf – spores of coprophilous fungi, as a proxy for domestic herbivores, cu – last cultivation records, pd – partial deforestation, td – total deforestation. Red arrows indicate migration events from Raraku to the other catchments.
6. Google Earth image of the SW sector of Kao crater showing the ritual village of Orongo with its typical oval stone dwellings (see Fig. 2 for location). White dots indicate the approximate location of coring sites that provided paleoecological evidence of terrace cultivation on lakeshores below Orongo (Horrocks et al., 2012b, 2013).
7. Examples of petroglyphs in the ceremonial village of Orongo. Photo: V. Rull.

Figure 1

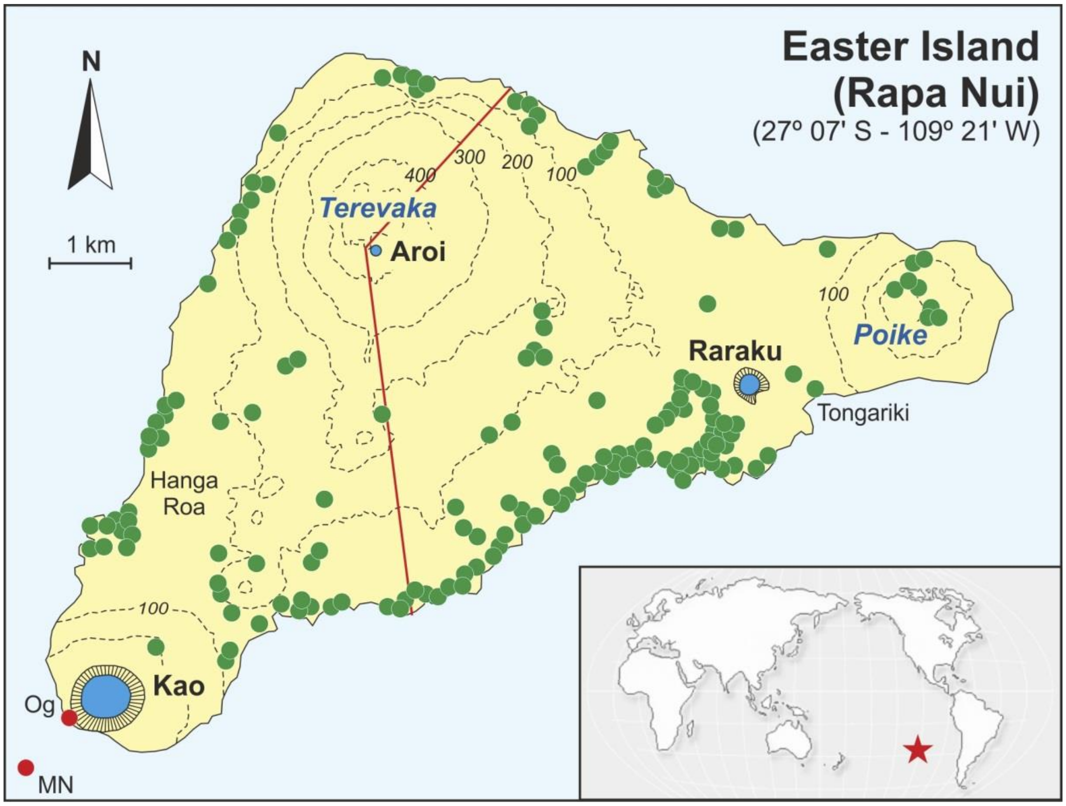

Figure 2

Figure 3

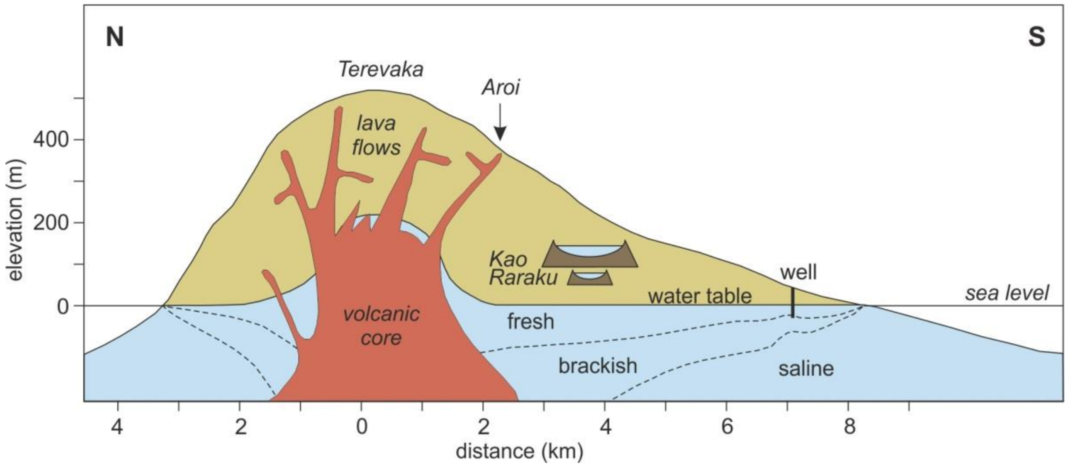

Figure 4

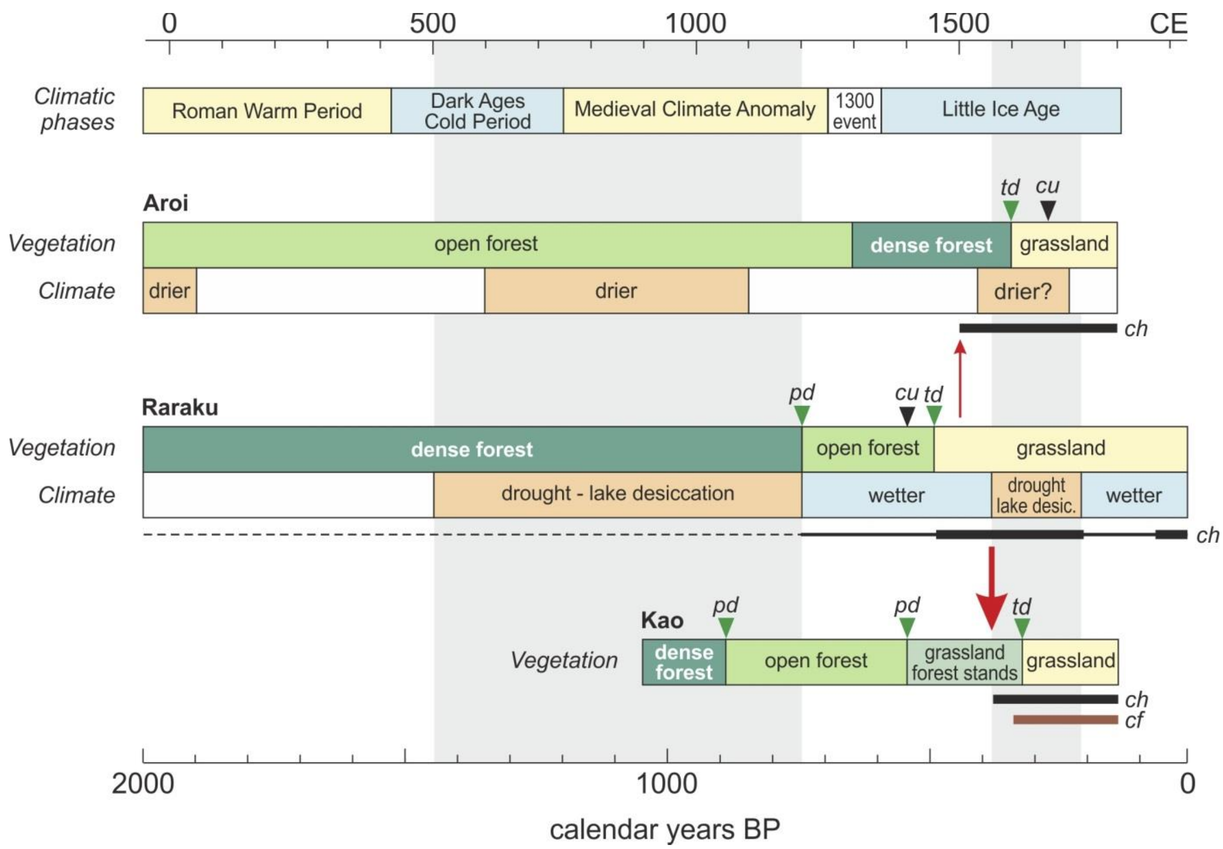

Figure 5

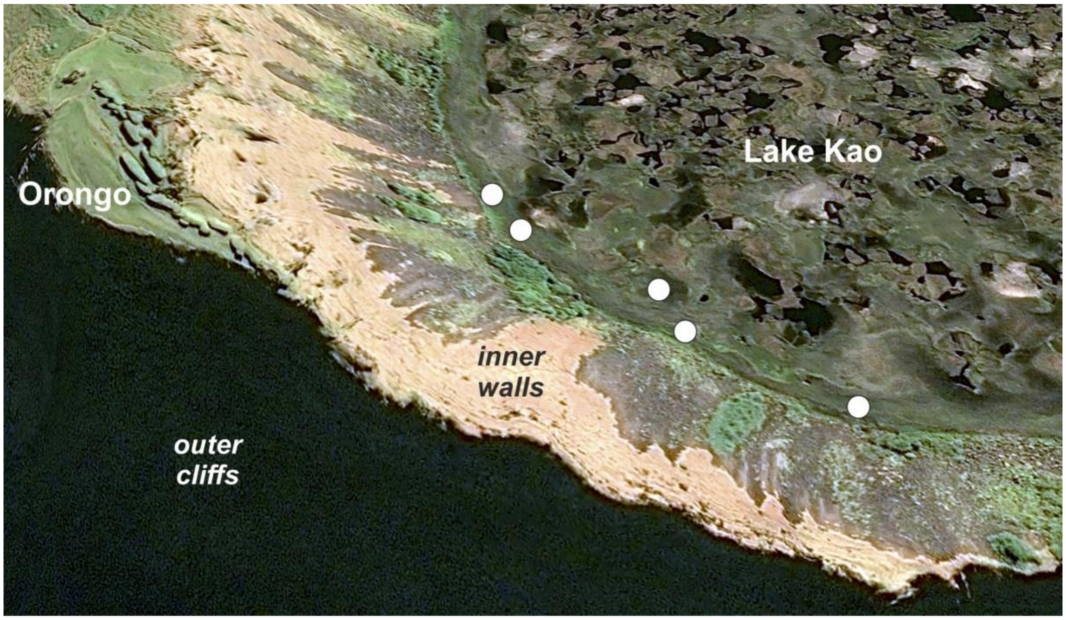

Figure 6

Figure 7