The deforestation of Easter Island (SE Pacific): a review

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Abstract

Easter Island deforestation has traditionally been viewed as an abrupt island-wide event caused by the prehistoric Rapanui civilization, which precipitated its own cultural collapse. This view emerges from earlier paleoecological analyses of lake sediments showing a sudden and total replacement of palm by grass pollen shortly after Polynesian settlement (800-1200 CE). However, further paleoecological research has challenged this view showing that the apparent abruptness and island-wide synchroneity of forest removal was an artifact due to the occurrence of a sedimentary gap of several millennia that prevented a detailed record the replacement of palm-dominated forests by grass meadows. During the last decade, several continuous and chronological coherent sediment cores encompassing the last millennia have been retrieved and analyzed, showing a very different picture. According to these analyses, deforestation was not abrupt but gradual and took place at different times and at different rates, depending on the site. Regarding causes, humans were not the only responsible for forest clearing as climatic droughts, as well as climate-human-landscape feedbacks and synergies, also played a role. In summary, the deforestation of Easter Island was a complex process, heterogeneous in time and space, which took place under the action of both natural and anthropogenic drivers and their interactions. In addition, archaeological evidence shows that the Rapanui civilization was resilient to deforestation and remained healthy until European contact, which contradicts the occurrence of a cultural collapse. Further research should be aimed at obtaining new continuous cores and make use of recently developed biomarker analyses to advance towards a holistic view of the patterns, causes and consequences of Easter Island deforestation.

Keywords: Rapa Nui, forest clearing, cultural collapse, las millennium, climate change, drought, fire, human disturbance, agriculture, pollen analysis.

1. Introduction

Deforestation is a common feature linked to human settlement of forested areas. Oceanic islands are particularly sensitive to deforestation because of the difficulty of forest regeneration due to the physical isolation that prevents recolonization from other potential forest sources. Therefore, deforestation on these islands is usually irreversible. This has been the case of many Pacific Polynesian islands and archipelagos after human arrival (McGlone, 1983; Nunn, 2007; Prebble et al., 2008, 2009). The case of Easter Island (Rapa Nui), the easternmost Polynesian island and one of the most remote inhabited places on Earth (Fig. 1), has become iconic, as it has been considered an example of a cultural collapse purportedly caused by human overexploitation of natural resources, including the total removal of palm forests that dominated the island before human settlement. This cultural collapse of the ancient Rapanui civilization has been called ecocidal and has been used as a microcosmic model for the whole planet under the current exploitation practices (Bahn & Flenley, 1992; Flenley & Bahn, 2003; Diamond, 2005). Others propose that deforestation would have been caused by massive palm fruit consumption by Pacific rats (*Rattus exulans*), which would have hindered forest regeneration (Hunt, 2006, 2007). These rats were carried to the island by the first Polynesian colonizers, whose arrival has been situated between about 800 CE and 1200 CE, according to different authors -see Rull (2019a) for a review on Easter Island colonization). According to this view, deforestation did not cause a cultural collapse and the ancient Rapanui culture remained healthy until the arrival of first Europeans (1722 CE), when the Rapanui degradation initiated and finally collapsed due to slave trading and the introduction of alien epidemic diseases (Rainbird, 2002; Peiser, 2005). Regardless the cause, the island was completely deforested when the first Europeans landed on it, in 1722 (Zizka, 1991).

Different deforestation timing and rates have been proposed. The first estimations assumed that forest clearing took place in 600 years, between 800 CE and 1400 CE (Flenley & Bahn, 2003). Considering the surface of the island (164 km^2), deforestation rates would have been about 0.3 km^2 per year (km^2/y). Others proposed that deforestation occurred in 370 years (1280 CE to 1650 CE) (Mann et al., 2008), which give an estimate of 0.4 km^2/y. These estimations were based on paleoecological data, using pollen analyses of lake sediments. Other estimations, based on archaeological evidence, give similar numbers, as forest removal would have elapsed about 400 years (1200 CE to 1600 CE) (Hunt, 2006, 2007), yielding estimates of 0.4 km^2/y. If we consider that forests did not cover the whole island but about 70% of its surface (Mieth & Bork, 2012), these estimates should be reduced by 25%, which yields a range between 0.2 and 0.3 km^2/y. Although Easter Island deforestation is commonly viewed as a relatively rapid and abrupt process, these rates are insignificant compared to current worldwide estimations of 52,000 km^2/y of forest removal between 2000 and 2010 (FAO, 2012). At such rates, Easter Island would have been deforested in one or two days (Rull, 2016a).

Before European contact, the Rapanui people were prehistoric (they lacked writing), and Neolithic (they did not know metals). The typical megalithic anthropomorphic cult statues (moai) that characterized the ancient Rapanui culture (Fig. 2), still present and widespread across the island, were carved on soft tuff using instruments made of harder basalt called toki (Gioncada et al., 2010; Simpson et al., 2018). Other instruments were the obsidian bladed points with cutting edges (mata'a), which were first interpreted as spear points or similar weapons but recent studies suggest that they were used for more peaceful labors such as cultivation, ritual scarification (Lipo et al., 2016) and, notably, forest clearing, in combination with basalt adzes (Stevenson & Williams, 2018). Fire was also intensively used in deforestation, as supported by paleoecological records of charcoal increases associated to palm removal (Mann et al., 2008; Butler & Flenley, 2010; Horrocks et al., 2012a, b, 2015). Several reasons have been proposed for island´s deforestation, as for example collecting firewood or wood for dwelling and boat building, opening lands for cultivation or obtaining rolls for moai transportation, among others (Flenley & Bahn, 2003).

At the beginning, the only evidence for the existence of former forests was the Rapanui oral tradition, as interpreted by some earlier ethnologists (Mulloy, 1979), the first sound evidence emerged from palynological studies of lake sediments. The first available record of past woody vegetation consisted of pollen analyses from sediments of unknown age obtained by Thor Heyedahl in his 1955-56 expedition. These analyses were performed by palynologist Olof Selling but remain unpublished. The only available mention is by Heyerdahl who cited a personal communication of Selling reporting the common presence of pollen from composite and possibly a palm species that are now extinct (Heyerdahl & Ferdon, 1961). About 20 years later, John Flenley and his collaborators published the first systematic pollen records of sediment cores retrieved in the ~40,000-years-old sediments of the three permanent freshwater bodies of the island: the Aroi marsh and the lakes Kao (or Kau) and Raraku (Fig. 3). These analyses clearly demonstrated the continuous presence of palm-dominated forests until the last millennia, when they were replaced by present-like grass meadows (Flenley & King, 1984; Flenley et al., 1991). These results became paradigmatic and were (and still are) used to sustain the ecocidal hypothesis for the collapse of the ancient Rapanui culture.

Further research, however, has challenged this view and has suggested new scenarios for Easter Island prehistory. This paper reviews the developments of paleoecological research since Flenley's pioneer studies, with emphasis on the potential causes of forest clearing and the spatiotemporal deforestation patterns. Relevant research questions are: was the deforestation abrupt or gradual? Was the deforestation synchronous and island-wide, as proposed by the pioneer studies? Or, on the contrary, it occurred at different times and with different rates, depending on the site? Was the deforestation entirely anthropogenic? Did environmental change play some role on forest clearing? The review begins with a characterization of the outstanding vegetation shift from the former forests to the modern-like open vegetation. Then the spatio-temporal deforestation patterns are analyzed and, finally, the potential causes for such patterns are discussed, with emphasis on human activities and environmental change.

2. From ancient forests to present-day vegetation

Easter Island's forests were totally removed without leaving a trace, there is no living witness of their composition and physiognomy. All we know about these ancient forests has been inferred from pollen and fossil wood analysis and knowledge about the modern features of the involved taxa. The dominant palm, however, could not be identified and remains a mystery. Human introductions have been significant, especially after European contact; therefore, present-day vegetation is very different from that growing on the newly deforested island. This section briefly summarizes the available knowledge on early forest composition and the main features of modern vegetation, with notes on the main crops of the ancient Rapanui civilization and the historical post-contact human introductions.

2.1. The ancient forests

The first inferences based on pioneer pollen analyses (Flenley & King, 1984; Flenley et al., 1991) provided a general picture on forest composition that has not changed through time. The abundance of palm pollen on sediments (typically 40-70% in Raraku and Kao) strongly suggested that these forests were dominated by a palm tree species but the commonness of the pollen type within the palm family prevented identification at genus o species level (Fig. 4). A first detailed morphological analysis suggested that the pollen could correspond to some species of the tribe Cocosoidae that, in the pacific region, is represented by the widespread *Coccos nucifera* (coconut) and *Juabea chilensis*, which inhabits the Pacific Chilean coasts (Dransfield et al., 1984) (Fig. 5). Further discoveries of palm nut endocarps significantly smaller than those of coconuts and trunk and root casts similar to those of *Jubaea* seemed to support the second possibility (Grau, 1998, 2001). However, this analogy was questioned on the basis of the manifest environmental differences between Easter Island and the Chilean coasts, and the possible affinity with *Juania australis*, and endemic palm of the Juan Fernández Islands, was suggested (Hunter-Anderson, 1998). Based on the endocarp morphology, a new monospecific genus was described for the Easter Island palm called *Phascalococos disperta*, which is thought to be extinct (Dransfield et al., 1984). At present, the more common names for this palm are *Jubaea* and *Phascalococos*.

Palm pollen occurred together with pollen from several shrubs, which suggested the existence of a shrubby understory, whose main components would have been *Sophora* (Fabaceae), *Triumfetta* (Tiliaceae), *Macaranga* and *Acalypha* (Euphorbiaceae), *Coprosma* (Rubiaceae) and several unidentified Asteraceae, Myrtaceae and Urticaceae/Moraceae (Flenley & King, 1984; Flenley et al., 1991) (Fig. 4). The occurrence and abundance of these elements vary in space and time but they seem to have been usual components of palm-dominated forests. An interesting finding was the identification of charcoal fragments corresponding >20 woody taxa, found on three archaeological sites, with ages ranging from the early-14th to the mid-17th centuries (Orliac, 2000; Orliac & Orliac, 1998). It has been asked whether these taxa were part of the ancient forests, as suggested by the age of their charred remains. However, only four of these taxa (*Triumphetta, Sophora, Coprosma, Phascalococos*) had been found in previous palynological studies. The remaining taxa, notably *Caesalpinia* (Caesalpiniaceae), *Thespesia* (Malvaceae), *Broussonetia* (Moraceae), *Sapindus* (Sapindaceae), *Psydrax* (Rubiaceae), *Elaeocarpus* (Elaeocarpaceae), *Myrsine* (Myrsinaceae), *Syzygyum* (Myrtaceae), *Pittosporum* (Pittosporaceae), *Alphitonia* (Rhamnaceae) and *Premma* (Verbenaceae), were absent from palynological records, suggesting that they were not part of the ancient forests. Alternative explanations are that these taxa were planted by Polynesian colonizers or were driftwood fragments utilized as firewood (Zizka, 1991).

Besides composition, forest cover has also been discussed. Although not explicitly stated, the first palynological works seemed to implicitly assume that Easter Island was entirely forested. The first (and the only available to date) quantitative estimation of forest cover was based on the present spatial distribution of root casts and charred palm trunks. Extrapolating the density of these features in the better preserved sites, it was estimated that, prior to deforestation, about 70% of the island would have been covered by dense forests containing about 16 million palm trees (Bork & Mieth, 2003; Mieth & Bork, 2012) (Fig. 5). A different view considered that the pollen signal was compatible not only with a fully (or mostly) forested island but also with other scenarios, including a mosaic vegetation pattern with forests restricted to sites with permanent freshwater such as lakes, marshes and coastal areas with high freshwater tables (Rull et al., 2010). The lack of modern analogs for these forests and the uncertain identity of the extinct palm that dominated them prevent a sound landscape reconstruction of Easter Island prior to deforestation.

2.2. Prehistoric agriculture

After Polynesian settlement (800 to 1200 CE), Easter Island's forests coexisted with crops. It has also been suggested that the forest was managed to obtain palm sap for sugar and other nutritious substances but this is based on the modern use of *Jubaea chilensis* in central Chile and needs empirical confirmation (Bork & Mieth, 2003). Archaeological evidence has shown that the ancient Rapanui did not practice extensive cultivation and widespread irrigation practices, crops were restricted to small (meter-scale) garden features called *manavai*, whose water supply was heavily dependent on rainfall (Hunt & Lipo, 2011; Puleston et al., 2017). To minimize evaporation and erosion, the *manavai* were protected from wind and surficial runoff by rock walls up to 2 m high and soils were covered by rocks to preserve moisture and nutrients, a practice called lithic mulching (Wozniack, 1999). Chemical analyses of agricultural soils suggest that they were more nutrient-rich than non-gardened soils, likely due to mulching-reduced leaching or active releasing of household organic matter (Hunt & Lipo, 2011; Ladefoged et al., 2010). The first estimations using satellite imagery identified more than 2500 *manavai*-like cultivation structures, for a total of 16.5 km^2, which represents 10% of the island's surface (Hunt & Lipo, 2011). Later, these numbers were upgraded to 13% of the coastal zone and 19% of the island surface (Ladefoged et al., 2013). During the first 500 years of human occupation, cultivation was carried out along the coasts and 1-2 km inland and the main volcanic peaks (Kao, Pike and Terevaka) were likely forested; however, after ~1500 CE, these forests were also replaced by *manavai* structures (Mieth & Bork, 2005). Recent investigations have shown that these agricultural practices continued, with no significant decline, until European contact (Mulrooney et al., 2013; Stevenson et al., 2015). Besides these main dryland cultivation practices, paleoecological evidence for local terrace cultivation has also been found on the shores of wetlands such as lakes Kao and Raraku and the Aroi marsh, where local irrigation systems possibly existed (Horrocks et al., 2012a, b, 2015).

Microfossil (pollen, phytolith, starch) analysis of both dryland soils and wetland sediments has allowed identification of the main plants of Polynesian origin cultivated prior to European contact, including mahute or paper mulberry (*Broussonetia papyrifera*; Moraceae), taro (*Colocasia esculenta*; Araceae), ti (*Cordyline* *fruticosa*; Asparagaceae), yam (*Dioscorea alata*; Dioscoreaceae), kumara or sweet potato (*Ipomoea batatas*; Convolvulaceae), ipu kaha or bottle ground (*Lagenaria siceraria*; Cucurbitaceae) and maika or banana (*Musa* sp.; Musaceae) (Horocks et al., 2016). The first Europeans who landed on Easter Island in 1722 documented the cultivation of bananas, sweet potatoes, yams and also sugar cane (*Saccharum officinarum*; Poaceae). The case of sweet potato is especially interesting, as its cultivation and consumption has been considered instrumental for the flourishment of the prehistoric Rapanui civilization, between about 1200 CE and 1500 CE (Fischer, 2005; McCall, 2009). The presence of this plant, of tropical American origin, on Easter Island well before the European discovery of America (1492 CE) has questioned the traditional paradigmatic views on two relevant research topics, namely the origin of the first Easter Island settlers and the possibility of Polynesians to have reached America some centuries before the Europeans (Rull, 2019a).

2.3. Modern vegetation

According to the available pollen records, deforested lands were initially covered by extensive, species-poor grass meadows, with aquatic or semi-aquatic plants –mainly sedges of the *Scirpus* type and *Polygonum* (Polygonaceae)- in flooded terrains (Flenley & King, 1984; Flenley et al., 1991). Today, the situation is very different as post-contact introductions and land management have deeply changed the island's ecosystems leading to a fully anthropic landscape. Detailed accounts of historical developments and landscape transformations are available elsewhere (McCall, 1981; Fischer, 2005; Hunt & Lipo, 2011). Today, the island is largely covered by grass meadows (90%), with very low forest (5%) and shrubland (4%) cover, pioneer and urban vegetation represent 1% of the surface (Etienne et al., 1982). Most meadows are dominated by two widely distributed grasses, *Sporobolus indicus* and *Paspalum scrobiculatum*, but the Terevaka uplands are dominated by the endemic grass *Axonopus paschalis* (heriki hare). Most forests are recent plantations of *Eucalyptus* spp. (Myrtaceae), introduced from Australia, and *Dodonaea viscosa* (Sapindaceae), carried from tropical America, as well as the native *Thespesia populnea* (Malvaceae). Shrublands are largely dominated by the invader *Psidium guajava* (Myrtaceae), also introduced from tropical America. Wetlands are dominated by *Scirpus californicus* (Cyperaceae) and *Polygonum acuminatum* (Polygonaceae), both occurring also in tropical America.

The angiosperm flora of the island is composed of ~180 species, of which 17% are autochthonous and 79% are introduced, the remaining 4% being of uncertain origin. Among the introduced species, almost the half (~48%) are considered to be naturalized. Globally, the families with more species are Asteraceae and Fabaceae. Only 3-4 extant species have been considered endemic to the island: *Axonopus paschalis* (Poaceae), *Danthonia paschalis* (Poaceae), *Sophora toromiro* (Fabaceae), and probably *Paspalum forsterianum* (Poaceae) (Zizka, 1991). Among them, the toromiro (*S. toromiro*) is considered to be extinct in its natural habitat for the past 50 years and is only maintained by cultivation in the island and also in several botanical gardens elsewhere (Maunder et al., 2000). Given the isolation of Easter Island, the ways in which the autochthonous species reached the island are of special significance. Interestingly, none of the autochthonous angiosperms has potential for wind dispersal, the main mechanisms being transport by birds (75%) and drift through seawater (25%) (Carlquist, 1967, 1974).

3. Spatio-temporal deforestation patterns

On Easter Island, there are only three volcanic craters containing permanent freshwater and sediments suitable for paleoecological studies. These ranos (local term to designate a volcanic crater with a permanent freshwater body inside) are widespread across the island and situated at different elevations, from the coastal lowlands to the inner uplands, thus covering a wide range of environmental conditions. Therefore, the integrated paleoecological study of these three sites is able to provide a general island-wide picture of long-term ecological trends. This section briefly explains the available pollen records for the last millennia to disclose deforestation timing and rates for each rano, in order to obtain an island-wide picture.

3.1. Rano Raraku

Rano Raraku contains a relatively small lake of lake (~300 m diameter, 2-3 m depth), situated at 80 m elevation, on the eastern coastal lowlands. The sedimentary infilling is at least 14 m deep, which corresponds to an age of 34 cal kyr BP (Rull, 2016c). The Raraku crater was the quarry where moais were carved and the center of the ancient Rapanui culture during its maximum development. This lake has been historically the preferred site for Easter Island's paleoecological studies for several reasons. First, it is the more accessible and the coring equipment can be easily transported by route. Second, the more chronologically coherent stratigraphic sequences have been obtained in this lake, whereas in Aroi and Kao, frequent age inversions have usually prevented the development of suitable age-depth models (Butler & Flenley, 2010; Horrocks et al., 2012a, b, 2015). Third, the more evident patterns of replacement of palm forests by grass meadows have been recorded in Raraku sediments. The drawback was that sedimentary records retrieved until a decade ago have an extensive stratigraphic gap embracing several millennia, including the time of interest for island's deforestation. This gap has been considered the main reason for which the first palynological records of deforestation appeared to be abrupt (Rull et al., 2013). In the first records, this gap was of 7 millennia or more, extending from >7.5 cal kyr BP to about 0.5 cal kyr BP (Flenley & King, 1984; Flenley et al., 1991; Dumont et al., 1998). Further studies reduced the hiatus to about 3500 years (~4 cal kyr BP to ~0.5 cal kyr BP) (Mann et al., 2008; Sáez et al., 2009) but the last millennia, when the island was deforested, remained hidden. A more recent palynological analysis showed an abrupt deforestation and an equally rapid grass expansion between 1.86-1.63 cal kyr BP and 0.63-0.51 cal kyr BP, coinciding with a sudden increase of charcoal, as a proxy for fire, and the first signs of terrace cultivation using taro, sweet potato, bananas and possibly bottle gourd Horrocks et al., 2012a). In this case, the sedimentary hiatus occurred just before those dates and embraced about 8,000 years.

An almost continuous and chronologically coherent Raraku sequence (RAR-08) was retrieved a few years later, which encompassed the last 3.7 cal kyr with only two minor centennial-scale gaps (Cañellas-Boltà et al., 2013) (Fig. 6). This sequence showed that the first deforestation event took place at about 450 BCE and proceeded gradually until about 1550 CE, with two major accelerations, one at ~1200 CE and another at ~1450 CE (Fig. 7). Forest retraction was continuous, no regeneration phases were observed. Grass meadows followed an inverse trend, paralleled by charcoal. Fire incidence was small until about 1200 CE, when significantly increased coinciding with the major deforestation pulse. Grass and fire trends largely coincided with those of *Verbena litoralis* (Verbenaceae) (Fig. 4), a weed of American origin, suggesting that humans would have been actively involved in island's deforestation. The potential significance of *V. litoralis* for the colonization timing and the origin of the first settlers are discussed elsewhere (Rull, 2019a). This reconstruction supported the view that the hitherto assumed abruptness of forest clearance was an artifact caused by the big sedimentary gap of previous sequences. Using the palm pollen percentage as a rough estimation of the forest cover, the latest Raraku record suggests that deforestation proceeded at a general rate of about -4% per century (Rull et al., 2015), which is far from being instantaneous. If we consider only the last millennium, when deforestation rates significantly accelerated, rates increase to -9% per century.

3.2. Rano Aroi

Rano Aroi is a mire of ~150 m diameter situated at 430 m elevation in the northern Terevaka uplands. The mire infilling is predominantly peat and is at least 16 m thick in the center, which represents an extrapolated age of approximately 70,000 years (Rull, 2016c). The first Aroi records did not show the palm dominance observed in Raraku for the last ~40,000 years and, therefore, no deforestation events were recorded. The whole record was dominated by grasses, followed by some ferns and shrubs and it was suggested that palm forests were restricted to lowlands and Aroi was near the uppermost treeline, where palm trees were scattered among shrublands and marshes (Fenley & King, 1984; Flenley et al., 1991). In addition, no dates below ~2 ^{14}C kyr BP were measured, which was interpreted in terms of vertical sediment mixing by human disturbance in the search of freshwater. As a consequence, the usefulness of the Aroi sediments to reconstruct the vegetation history of the las millennia was questioned (Fenley & King, 1984; Flenley et al., 1991) and the site was not further cored for about three decades.

A recent sedimentary sequence confirmed the former interpretation of near-treeline vegetation (although palms were more abundant than in previous analyses) and obtained a fairly consistent chronology for the last 1000 years but not for the former 11 millennia, where age inconsistencies were frequent (Horrocks et al., 2015). Unfortunately, the temporal resolution of the last millennium (one four samples, or one sample every 250 years) was not enough for a detailed reconstruction. In spite of this, the first signs of terrace cultivation were proposed to have found at about 280 cal yr BP (1670 CE). Cultivated plants included taro, paper mulberry and bananas but sweet potato was remarkably absent, probably due to elevation. Another sedimentary sequence was obtained in a small swamp near Rano Aroi (Rano Aroi Iti) embracing the last ~1500-1300 cal kyr BP. During this time, meadows were dominant and experienced a slight increase paralleled by a similar forest decline. Charcoal was present throughout the core but no evidence for cultivation was found. The pollen of the American herb *Sisirynchium* (Iridaceae) was present since the beginning and occurred all over the core, suggesting that this plant may have been introduced by 450-650 CE, more than a millennium before European contact (Horrocks et al., 2015). This case is similar to that of *Verbena* in Rano Raraku (Cañellas-Boltà et al., 2013) and the same considerations on the first Easter Island settlers and the Polynesian discovery of America are valid here.

A fully continuous and chronologically coherent sedimentary record was obtained later in Aroi (ARO08-02) encompassing the last 2.7 cal kyr, which was analyzed at multidecadal resolution of (Rull et al., 2015) (Fig. 6). The general dominance of open grass vegetation with palms and shrubs was confirmed once more but this pattern remarkably changed during the last centuries (Fig. 7). Indeed, palm forests underwent a rapid expansion (50% of palm pollen per century) starting at about 1400 CE and peaking slightly after 1500 CE, which coincided with a similar decrease of grasslands, indicating that the site was rather forested. The deforestation began by 1520 CE and was complete ~80 years later, by 1600 CE, coinciding with an abrupt fire increase that ceased when the site was fully deforested and covered by grassland meadows (Rull et al., 2015). During this event, forest clearing proceeded at a rate of over -70% of palm pollen per century, which is ten times that of Raraku.

3.3. Rano Kao

Rano Kao contains the largest lake of the island, with ~1250 m diameter, situated at 110 m elevation in the southwestern end of the island. The surface of this lake is a mosaic of open water and floating mats of aquatic vegetation up to 3 m depth, overlying a water column of approximately 10 m depth. The sediments are at least 21 m deep and their maximum measured age is about 34 cal kyr BP (Rull, 2016c). The pioneering analyses by Flenley and co-workers (Flenley & King, 1984; Flenley et al., 1991) were not conclusive due to dating inconsistencies, probably due to the sinking of floating mats and their mixing with lake sediments (Butler et al., 2004). A further core retrieved by the sane team (KAO2), covering almost all the Holocene, was successfully dated and analyzed for pollen and charcoal (Butler & Flenley, 2010). Two deforestation events associated to coeval charcoal increases were recorded in this core, one at 1900-1850 cal yr BP (50-100 CE) and another occurred during the last 600 cal yr BP but its chronology is difficult to specify owing to age inversions. Between them, a phase of forest regeneration occurred. Despite the lack of dating precision, the second deforestation event seems to be consistent with the classic view of deforestation after Polynesian settlement but the first occurred between 700 and 1100 years before Polynesian arrival, which adds support to a hypothetical earlier colonization, as suggested by the presence of *Verbena* and *Sisyrinchium* pollen in the Raraku and Aroi sequences, respectively (Cañellas-Boltà et al., 2013; Horrocks et al., 2012a).

The first continuous and chronologically coherent Kao record encompassing the last millennia (KAO05-3A) was obtained in the floating mat (Gossen, 2007); however, pollen analyses similar to those from Raraku and Aroi and useful to unravel deforestation patterns are still unavailable. More recently, pollen and other microfossil (Phytoliths, starch) and physical (Fourier Transformed Infrarred or FTIR) microscopic analyses revealed the occurrence of a major deforestation events and provided evidence for terrace cultivation, but age inconsistencies prevented the development of a reliable age-depth model (Horrocks et al., 2012b). Recently, another core (KAO08-03) was retrieved in the floating mat and studied palynologically (Rull et al., 2018; Seco, 2018) (Fig. 6). This core extended from about 1000 to 300 cal yr BP and its analysis showed a gradual deforestation trend between about 1050 CE and 1600 CE, with three main pulses at 1050 CE, 1350 CE and 1600 CE (Fig. 7). The first two were more intense and forest regeneration trends were recorded between them. After the second pulse, forests almost disappeared but then experienced some recovery, which was interrupted by the 1600 CE deforestation pulse, which permanently removed palm forests from Rano Kao. Overall, this deforestation trend occurred at average rates of -9% palm pollen per century, which coincides with Raraku. Taken individually, the three Kao deforestation pulses occurred at rates of -30% to -50%, which are about the half of the recorded in the abrupt Aroi deforestation. Regeneration phases were slower (-5% to -10%). The first deforestation pulse was not associated to a fire increase, the second occurred at the same time that a moderate fire event and the third took place at the beginning of the major fire event recorded in the diagram. This, together, with the similar increase in *Soporomiella* fungi spores, indicator of human presence (Van Geel et al., 2003), will be discussed in the section dealing with deforestation causes.

3.4. Overview

The above discussion clearly shows that deforestation patterns across the island were heterogeneous in space and time and occurred at different rates, according to the site. Therefore, the proposal of a single and abrupt island-wide deforestation event, as proposed by the classic paradigm, was likely due to sedimentary artifacts, notably the occurrence of a major hiatus in the first cores retrieved. The improvement of knowledge on spatio-temporal deforestation patterns has been possible after the intensification of lake coring and paleoecological analyses efforts occurred in the last decade, which has resulted in continuous and chronologically coherent sequences of the last millennia for all Easter Island's sedimentary basins. Another interesting finding is that some forests exhibited regeneration trends between consecutive deforestation events. This occurred in Rano Kao and also in Rano Aroi, although in this case regeneration was not preceded by a deforestation pulse. On the contrary, no forest regeneration was observed in Rano Raraku. This may suggest that deforestation pressure was continuous in some places (Raraku) and intermittent in others (Kao), which adds more heterogeneity to the already irregular deforestation scenario. The causes for such a heterogeneous deforestation scenario in time and space should be different than those for a hypothetical single, abrupt and island-wide forest clearance event, as discussed in the next section.

4. Natural and anthropogenic deforestation drivers

It is not unusual to attribute historical socio-ecological collapses to the action of single punctual causes. Sometimes the assumed causes are singular natural environmental changes that surpass the adaptation capacity of ecosystems and/or human societies (environmental determinism), whereas in other cases, the purported drivers are anthropogenic (human determinism). On Easter Island, human determinism has traditionally been the norm, as deforestation and the Rapanui cultural collapse have been attributed to anthropogenic causes such as prehistoric overexploitation, introduction of exotic species, internal conflicts and wars, or post-contact genocide. Climate changes have rarely been considered as potential causes for cultural change but this view has changed during the last decade. In this section, we will analyze the potential role of natural and anthropogenic drivers on island's deforestation and its cultural consequences. Rather than a shift from human determinism to environmental determinism, this should be viewed as an attempt to consider all possible drivers as well as their interactions, in the form of feedbacks and synergies. This methodology has been called the strong fuzzy EHLFS (Environment-Humans-Landscape Feedbacks and Synergies) approach and uses a multiple-working-hypotheses framework and the strong inference method of hypothesis testing (Rull, 2018b).

4.1. Climate change on Easter Island during the last millennia

The lack of empirical evidence of climate changes on Easter Island was used in the past to dismiss a potential role for climate on the purported prehistoric socio-ecological collapse (Diamond, 2005). Some authors have speculated about the possibility of droughts during the Little Ice Age (LIA) (McCall, 1993), the potential influence of ENSO variability on Easter Island (Orliac & Orliac, 1998; Nunn, 2000; Orliac, 2000; Nunn & Britton, 2001; Stenseth & Voje, 2009) or the Late Holocene climatic instability on the disappearance of palm forests (Hunter-Anderson, 1998). Others denied such possibility arguing that ENSO and other climatic systems do not produce enough variability to significantly affect Easter Island's climate (MacIntyre, 2001; Genz & Hunt, 2003; Junk & Claussen, 2011). However, most of these proposals were based on extrapolations based on modern climates and no paleoeclimatic evidence was available to support either one or another view. The first evidence of changing climates was obtained by pollen analysis of sediments from Rano Raraku (RRA5) spanning from 28 to 10 cal kyr BP, which includes the Last Glacial Maximum (LGM), the coldest worldwide event before the Holocene, when average southern Pacific temperatures were up to 6 °C cooler than at present. However, on Easter Island, LGM estimations based on the Raraku RRA5 core were only ~2 °C cooler than at present (Azizi & Flenley, 2008). It was inferred that, if the coolest glacial phase was only 2 °C below present temperatures, Holocene temperature shifts might have been negligible and, hence, temperature shifts were unlikely to have driven last-millennium ecological changes, as for example deforestation. However, this did not dismiss the potential influence of eventual moisture changes, mainly droughts, as proposed initially (McCall, 1993).

Further studies interpreted the Raraku millennial-scale sedimentary gap mentioned above as the evidence for an extended drought that dried out the lake and could have had a role in the deforestation, together with human disturbance (Mann et al., 2008; Sáez et al., 2009). However, the finding of fairly continuous sedimentation in other cores of the same lake challenged this view. In one of these cores (RAR 08), two minor gaps remained that were interpreted as evidence for lake desiccation due to climatic droughts. The first occurred between 500 CE and 1200 CE, during the Medieval Climate Anomaly (MCA), and the second took place between 1570 CE and 1720 CE, during the LIA (Cañellas-Boltà et al., 2013). The sedimentation was continuous in Rano Aroi but two phases of vegetation opening occurred well before human settlement and not associated to fire events suggested the occurrence of two phases of drier climates at 300 BCE-50 CE and at 600-1100 CE, the later coinciding with the MCA drought recorded at Raraku. The abrupt deforestation of Rano Aroi coincided with the Raraku LIA drought (Rull et al., 2015).

4.2. Climate-human-landscape interactions

The available empirical evidence for climate shifts, mostly droughts, spatio-temporal deforestation patterns and trends, and human presence and activities, can be integrated into a holistic, non-deterministic scenario for Easter Island deforestation and its potential causes (Fig. 8). It is hoped that further research will improve this framework but a synthesis of the information available to date seems pertinent to provide a unified multi-hypotheses research framework for future studies. The following is a proposal in this sense, which is subdivided into two main phases: the pre-Polynesian settlement phase (before 800-1200 CE) and the last millennium.

4.2.1. Pre-Polynesian settlement phase

Forest clearing began in Raraku by 450 BCE but the impact remained low until about 1200 CE. During this very long phase (almost 1700 years), meadows slightly expanded but the landscape continued to be forested Cañellas-Boltà et al., 2013). The appearance of *Verbena*, the gentle fire increase and the lack of evidence for climate change favor an anthropogenic explanation for this first deforestation pulse, possibly linked to Amerindian presence. The next deforestation event was recorded at Rano Kao by 100 CE and was linked to a conspicuous fire increase, thus suggesting human disturbance (Butler & Flenley, 2010). Again, no evidence of climatic change was recorded. By those times, Rano Aroi was not forested but the occurrence of *Sisyrinchium* since 450-650 CE reinforces the possibility of Amerindian colonization (Horrocks et al., 2015). The whole picture suggests that the first forest disturbance on Easter Island may have been caused by Native Americans, between about 450 BCE and 650 CE. However, no archaeological evidence has been found to support such hypothesis, which suggests that human presence on the island was possibly sporadic and/or intermittent and a true autochthonous culture was not established. Another possibility is that American plants were not introduced by Native Americans but by Polynesians –whose superior navigation ability has been clearly demonstrated by the colonization of the entire Pacific Ocean from west to east during the last 3000-4000 years (Kirch, 2010)- in eventual back-and-forth voyages to America (Rull, 2019a). Such explanation has been proposed for the introduction of sweet potato in Polynesia (including Easter Island) and the cases of *Verbena* and *Sisyrinchium* could be similar. In this case, the first deforestation steps could have also been caused by ephemeral Polynesian settlements. Regardless the explanation, it seems clear that the full occupation of the island and the development of an island-wide autochthonous culture did not occur until the last millennium, when Polyenisans permanently settled the island.

4.2.2. The last millennium

After a long period (~400-600 years) of apparent forest stability –or lack of evidence of forest disturbance- the first deforestation pulse during or after Polynesian settlement was recorded in Rano Kao, at about 1050 CE (Rull et al., 2018; Seco, 2018). The occurrence of *Sporormiella* spores –a genus of coprophilous fungi living in the dung of domestic herbivores (Van Geel et al., 2003)- suggests human presence. However, the small amount of these spores and the absence of fire indicate that human occupation may have been low and probably not enough to cause a deforestation event like the recorded. This occurred during the MCA drought that desiccated Lake Raraku and, hence, climate may have been the main responsible for the 1050 CE Kao forest clearing. The fact that Rano Aroi vegetation was apparently not affected by this drought could be due to the maintenance of wetter conditions due to its higher elevation and the occurrence of an elevational precipitation gradient, which today is of almost 200 mm/100 m elevation (Puleston et al., 2017).

The next deforestation episode occurred in Raraku at ~1200 CE, just after the MCA drought, under sustained, although moderate, fire pressure (Cañellas-Boltà et al., 2013). The occurrence of wetter climates, more favorable for forest growth, suggests that this deforestation pulse was of anthropogenic origin. Forest retreat was continuous despite fires did not significantly increase, which suggests the existence of positive feedbacks amplifying forest response to sustained fire incidence. During the same time, the Kao forests were recovering, likely due to favorable climates and the absence of human pressure, as indicated by the lack of fires and coprophilous fungi (Rull et al., 2018; Seco, 2018). However, this forest regeneration was interrupted by another deforestation episode (1350 CE), likely anthropogenic, coinciding with a charcoal peak and the return of *Sporormiella* spores (Rull et al., 2018; Seco, 2018). Rano Aroi continued to be devoid of humans and the significant forest expansion recorded between about 1300 CE and 1500 CE was likely due to the occurrence of wetter climates (Rull et al., 2015).

Rano Raraku forests disappeared after a last deforestation event occurred by 1450 CE, coinciding with a significant fire exacerbation supporting human deforestation (Cañellas-Boltà et al., 2013). At the same time, human pressure declined in Rano Kao and its forests, which had been almost removed by the 1350 CE deforestation pulse, experienced a new regeneration trend, although less intense than the former (Rull et al., 2018; Seco, 2018). During the same time, Rano Aroi was truly forested for the first time and its forests turned to be the most dense and extensive of the whole island, due to the almost total deforestation of Raraku and Kao. However, the situation changed by 1570 CE, when a sudden deforestation totally removed these forests (Rull et al., 2015). This coincided with an intense fire exacerbation suggesting anthropogenic causes but the LIA drought would have acted synergistically by favoring forest flammability and preventing regeneration.

The last deforestation event of the island irreversibly removed the Kao forests by 1600 CE, coinciding with the largest human occupation of this crater, as indicated by the significant increase of fires and *Sporormiella* spores. This has been associated with the foundation of the ceremonial village of Orongo at the crest of the Kao crater, which took place at 1600 CE (Robinsion & Stevenson, 2017), and replaced the Raraku quarry as the center of the prehistoric Rapanui culture. This geographical shift coincided with the end of the moai cult and the onset of a totally different social, religious and political organization known as the Birdman cult (Rull, 2016b; Rull et al., 2018). It has been proposed that synergies between climate (drought, lake desiccation) and humans (deforestation) would have transformed the site into inhospitable badlands unable to support human activity and the moai industry, which was the main activity of the Rapanaui civilization by the time. This would have caused massive human migration to Rano Kao, likely the only freshwater source during the LIA drought (Rull, 2019b).

A comment seems pertinent regarding the possibility of Pacific rats as responsible for deforestation by preventing forest regeneration. This possibility was suggested by Hunt (2006, 2007) based on the finding of endocarps of the enigmatic palm species with marks of rat knowing. Mieth & Bork (2010) attributed this to the fact that these palm endocarps were found exposed in caves thus being accessible to rats for long time. These authors analyzed endocarps buried in situ within charcoal layers and only 10% had gnawing marks. Mieth & Bork (2010) also found evidence for forest regeneration by finding a second generation of palm root casts overlying an older layer with charred wood resulting from an earlier forest clearing dated to 1280-1390 CE. They concluded that rats did not hinder forest regerantion and, hence, they were not responsible for Easter Island's deforestation. Palynological evidence of forest regeneration found in Rano Kao and Rano Aroi, as reported in this paper (Butler & Flenley, 2010; Rull et al., 2015, 2018; Seco, 2018), are consistent with Mieth & Bork's (2010) conclusions.

General conclusions and further research

In response to the research questions raised in the introduction, the general deforestation of Easter Island was not abrupt, synchronous and island-wide, as proposed by pioneer paleoecological studies. Only one site (Aroi) was suddenly and totally deforested in less than a century, whereas in others (Raraku and Kao), deforestation was gradual and spiked by two or more accelerations at different times. Deforestation timing and rates were significantly different across the island. Regarding causes, some deforestation events could be linked to droughts, others to human activities and others to feedbacks and synergies between them. Therefore, Easter Island's deforestation seems to have been a largely heterogeneous process in time and space under the influence of both natural and anthropogenic drivers. In addition, archaeological evidence on cultivation practices have suggested that total island deforestation did not cause a cultural collapse and the Rapanui civilization was resilient to this landscape alteration shift, remaining healthy until European contact. The whole picture contrasts with the former ecocidal paradigm of an island-wide abrupt forest clearing caused exclusively by humans and opens a new, more complex perspective for forest removal and its causes, as well as the potential consequences for the Rapanui culture.

Further paleoecological efforts are still needed for a sound understanding of deforestation timing and patterns of Easter Island and its causes. Regarding coring, only one continuous and chronologically coherent sedimentary sequence is available for the last millennium at each site and more coring is required to confirm the first insights based on these sequences. The recent development of molecular analyses, especially biomarkers, may provide valuable information on climatic shifts and human activities. For example, the use of glycerol-dialkyl-glycerol-tetraethers (GDGTs) and *n*-alkanes from plant leaf waxes may provide detailed temperature and precipitation reconstructions, respectively (Eglington & Eglington, 2008). Regarding human presence and activities, the use of specific fecal lipids such as 5α-stanols and bile acids can inform on the presence of humans and/or ruminant livestock (Bull, 2002; D'Anjou et al., 2012). Molecular DNA analyses may also provide evidence for anthropogenic activities, by directly recording human presence and also the occurrence of plants and animals associated to human activities (cultivation, livestock, introduction of alien species) (Rawlence et al., 2014; Parducci et al., 2017). This is especially useful to complement pollen and other microfossil analyses (fungi spores, phytoliths, starch) and could provide crucial evidence for the identification of the unknown palm species that dominated Easter Island forests. Infrared spectral analyses (FTIR) have also been useful for microfossil identification in Easter Island sediments but its full potential has not yet fully developed. This is also a growing field of research that should be intensively used in the future. In addition to new coring campaigns and the use of novel molecular evidence, multidisciplinary collaboration is essential, not only within the different paleoresearch specialties but also among different scientific disciplines such as archaeology, anthropology, ethnology and history, among others (Rull et al., 2013). A constant in Easter Island research has been the individualistic behavior of these disciplines, which is contrary to the integrative nature of paleosciences and the complexity of environmental-landscape-human interactions (Rull, 2018a, b). Truly multidisciplinary studies are essential to progress toward a sound understanding of what really happened on Easter Island before European contact.

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Figure captions

1. Location map. A) Sketch map of the main Pacific islands and archiplegaos showing the position of Easter Island (red dot). West-east peopling trends from continental Asia are indicated by orange arrows (Kirch, 2010). B) Sketch map of Easter Island indicating the wetlands (ranos) cored for paleoecological studies (blue areas). Present-day planted forests, mainly of *Eucalyptus* (Myrtaceae) are indiecated by green areas. Elevation in meters.
2. Moai comples of Ahu Tongariki, near Rano Raraku, with the Poike cliffs at the background. These moai are up to 9 m high and 90 tons of weight. Photo: V. Rull.
3. Google Earth images of the three ranos cored for paleoecological analyses and its location on the island. The dark-green area at the center of the island are planted *Eucalyptus* forests. All cores retrieved historically in the three sites are shown (white dots) and the recent continuous and chronologically coherent sequences are highlighted by red dots and blue names. Redrawn from Rull (2016).
4. Selected representative pollen types from lake/marsh sediments. 1) unknown palm species, 2) Poaceae, 3) Cyperaceae, 4) Compositae, 5) *Polygonum*, 6) *Triumphetta*, 7) and 8) *Verbena litoralis*. 1 to 6 from Rano Aroi (Rull et al., 2015), 7 and 8 from Rano Raraku (Cañellas-Boltà et al., 2013).
5. *Jubaea chilensis* woodland at Parque Nacional La Campana, Chile. Licensed by Creative Commons Attribution 2.0 (https://commons.wikimedia.org/wiki/File:Jubaea_chilensis_(scott.zona).jpg).
6. Age-depth models of the continuous and chronologically coherent sedimentary records of the last millennia obtained in Rano Raraku, Rano Aroi and Rano Kao. Reproduced from Cañellas-Boltà et al. (2013) (Raraku) and Rull et al. (2015, 2018) (Aroi and Kao), with permission.
7. Synthetic diagrams of Rano Raraku, Rano Kao and Rano Aroi for the last millennium. Droughts are depicted as gray bands. Red triangles indicate deforestation pulses and forest regeneration trends are indicated by blue arrows. Raw data and full diagrams are in Cañellas-Boltà et al. (2013) (Raraku), Rull et al. (2018) and Seco (2018) (Kao), and Rull et al. (2015) (Aroi).
8. Spatio-temporal deforestation patterns of Rano Aroi, Rano Kao and Rano Raraku areas and their potential drivers after Polynesian settlement, using the information of Fig. 7. Forest cover is estimated by palm pollen percentage. The blue arrow indicates the migration of the cultural core of the Rapanui society from Rano Raraku to Rano Kao. See text for detailed explanations.

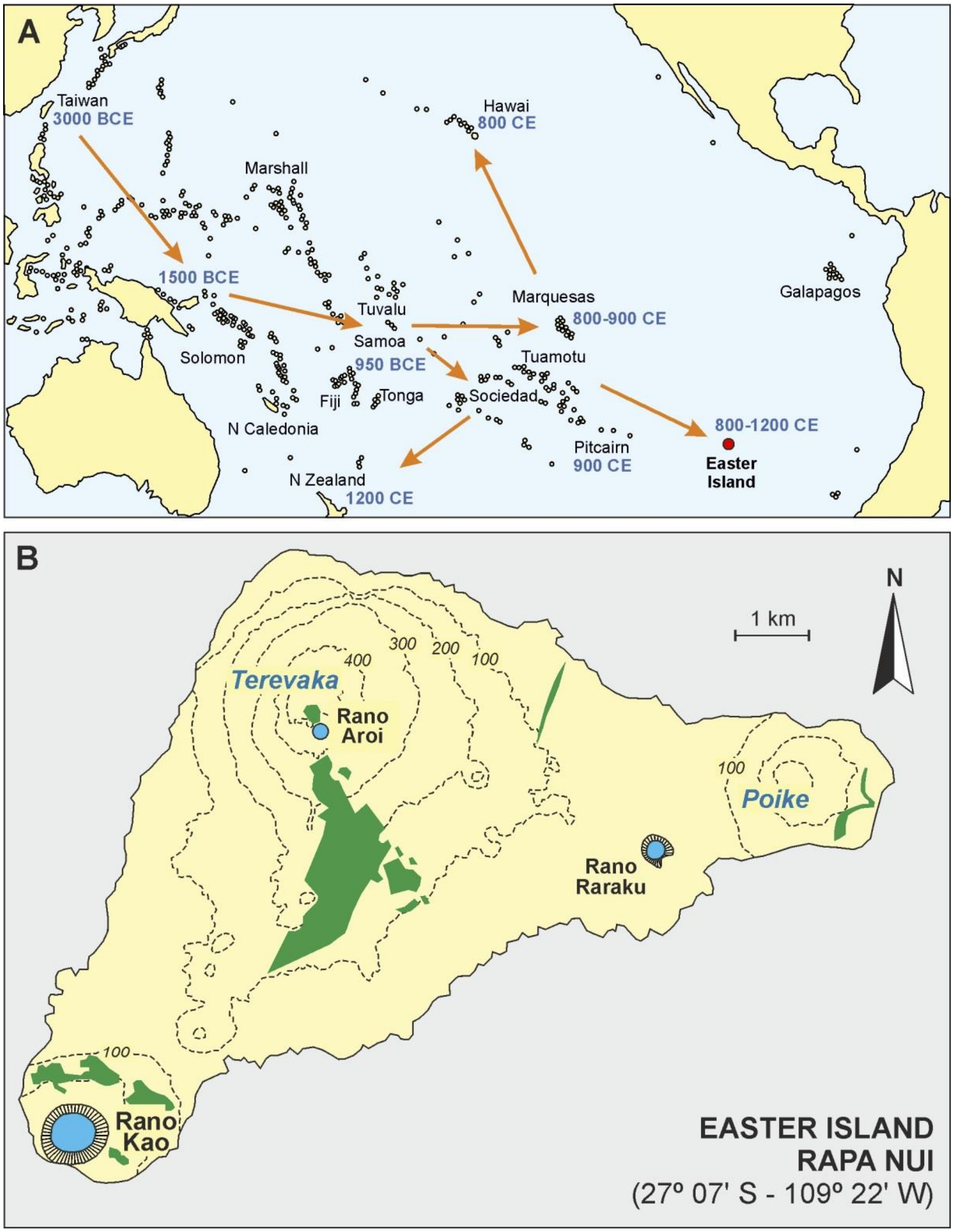
A
Taiwan
3000 BCE
1500 BCE
Marshall
Hawai
800 CE
Tuvalu
Samoa
950 BCE
Solomon
Fiji
Tonga
N Caledonia
N Zealand
1200 CE
Marquesas
800-900 CE
Tuamotu
Sociedad
Pitcairn
900 CE
800-1200 CE
Easter
Island
Galapagos
B
N
1 km
Terevaka
400
300
200
100
Rano
Aroi
Poike
Rano
Raraku
Rano
Kao
EASTER ISLAND
RAPA NUI
(27º 07' S - 109º 22' W)

Figure 1

Figure 2

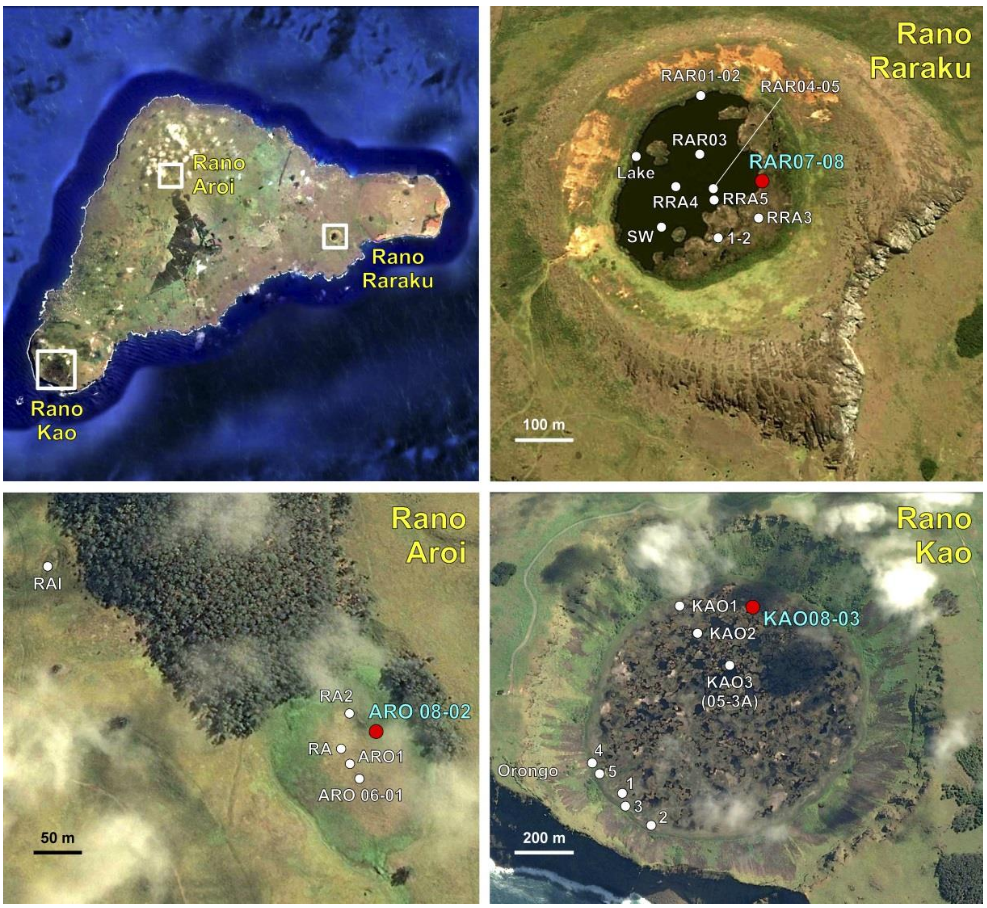

Figure 3

Figure 4

Figure 5

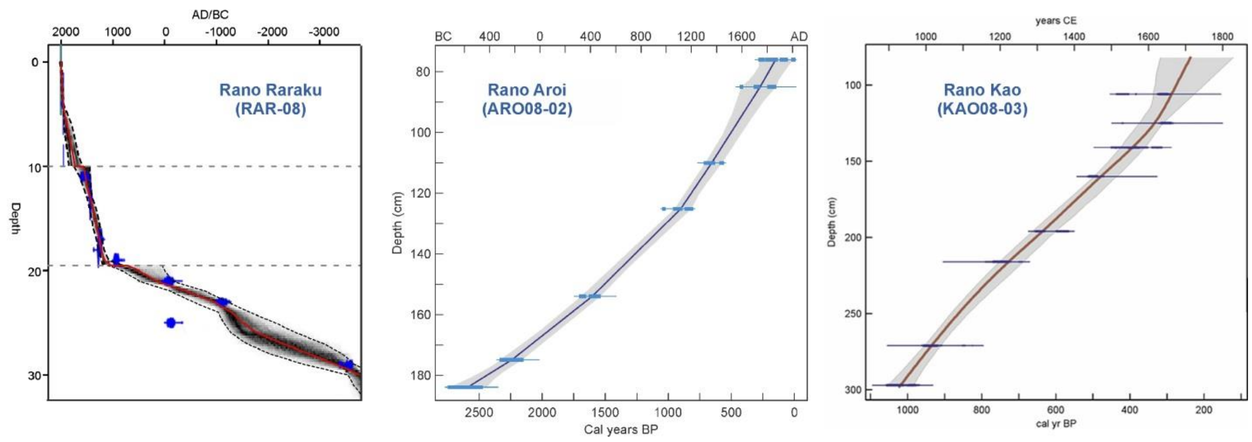

Figure 6

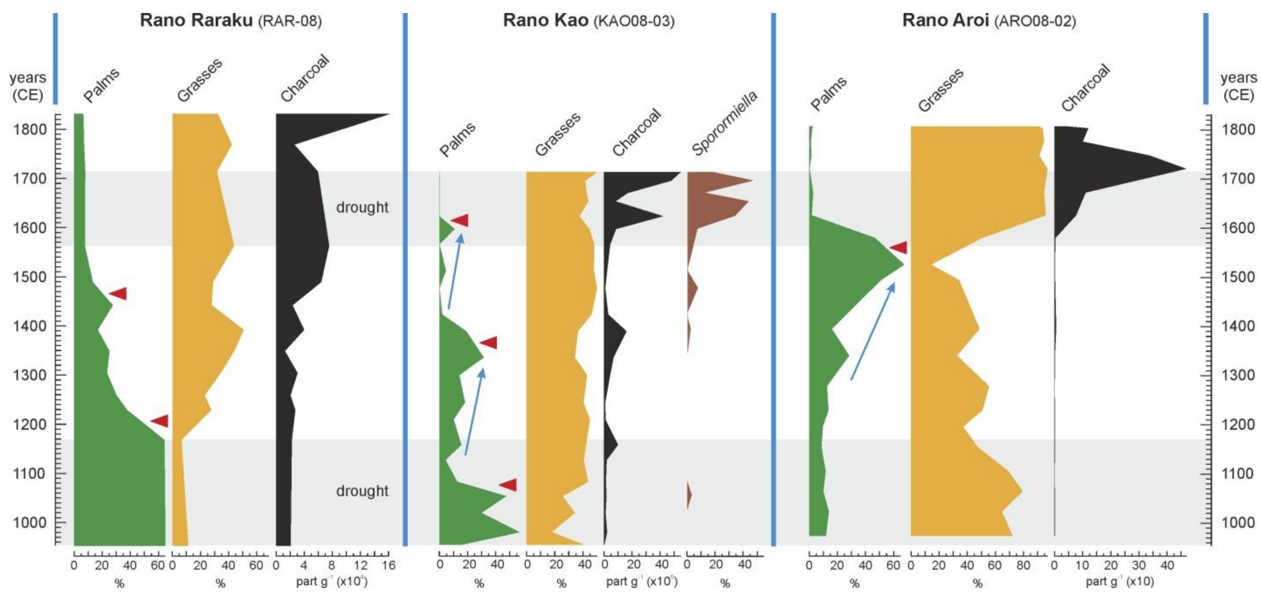

Figure 7

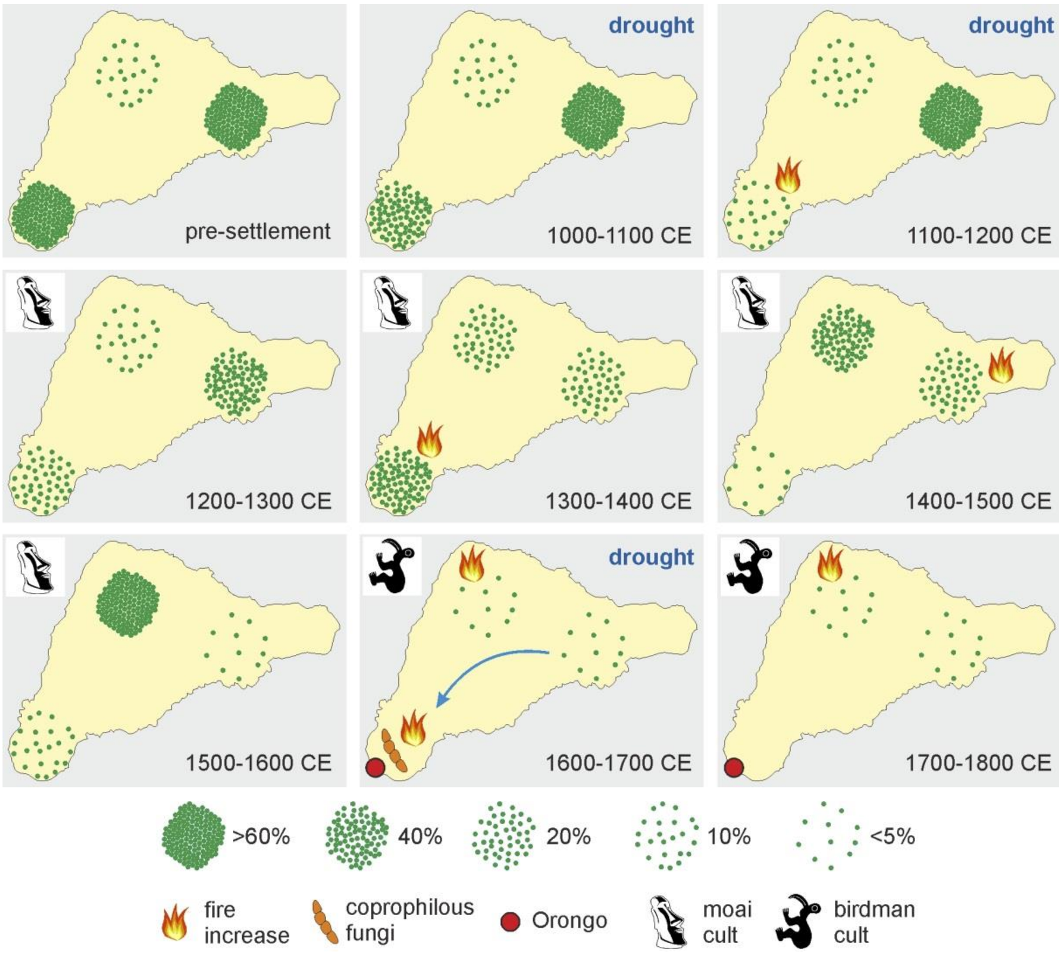
drought
drought
pre-settlement
1000-1100 CE
1100-1200 CE
1200-1300 CE
1300-1400 CE
1400-1500 CE
drought
1500-1600 CE
1600-1700 CE
1700-1800 CE
>60%
40%
20%
10%
<5%
fire increase
coprophilous fungi
Orongo
moai cult
birdman cult

Figure 8