



Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: <http://www.elsevier.com/locate/jas>

Humans, climate or introduced rats – which is to blame for the woodland destruction on prehistoric Rapa Nui (Easter Island)?

Andreas Mieth*, Hans-Rudolf Bork

Ecology Centre, Institute for Ecosystem Research, Christian-Albrechts-Universität zu Kiel, Olshausenstrasse 40, D-24098 Kiel, Germany

ARTICLE INFO

Article history:

Received 13 May 2009

Received in revised form

29 September 2009

Accepted 6 October 2009

Keywords:

Easter Island

Rapa Nui

Pacific islands

Deforestation

Rats

Palms

Jubaea chilensis

Environmental history

Ecocide

ABSTRACT

When the first Polynesian settlers arrived on Rapa Nui, about 70% of the island was covered with dense woodland in which *Jubaea* palms dominated. Our investigations of extended soil profiles provide evidence that more than 16 million palm trees grew on the island. Nearly all palms were removed by the 16th century. Teeth marks on nutshells of the *Jubaea* palms from the 13th or 14th centuries attest to the activity of Pacific rats (*Rattus exulans*) on Rapa Nui, which were probably imported there by the first Polynesians settlers. Did the rats perhaps prevent the germination of palm seeds and thus the regeneration of the dense palm woodland of Rapa Nui?

The results of our investigations refute this hypothesis and support the assumption that people cut the trees. Burned relicts of palm stumps and widespread burned soil layers containing charred endocarps of the palms testify to intensive slash and burn activities between 1250 AD and 1500 AD. However, in one area on Rapa Nui, evidence for regeneration of palm woodland following the first clearing was found. This finding provides evidence against a major rat impact. Furthermore, the *Jubaea chilensis* woodland in central Chile illustrates that small rodents and *Jubaea* palms can coexist. We conclude that people, not rats, were the dominant destroyers of the palm woodland on Rapa Nui.

© 2009 Elsevier Ltd. All rights reserved.

1. Rapa Nui and the destruction of its woodland

Rapa Nui (Easter Island) is the most eastern island of Polynesia, located at a distance of about 3700 km from South America. There was a general agreement amongst Rapa Nui scholars that the island was colonized by Polynesians no later than the end of the first millennium AD (e.g. Martinsson-Wallin, 2004; Vargas et al., 2006). This is currently doubted by Hunt and Lipo (2006), who assume a significantly later primary arrival of people around 1200 AD. However, despite (or because of) its isolation, the island underwent a dramatic ecological change between the date of Polynesian colonization and the “discovery” of the island by Europeans on April 5, 1722. The circumstances, causes, and triggers of these environmental changes are the subject of persistent scientific discussion.

Today, the surface of Rapa Nui's landscape is dominated by grassland and millions of stones. It has a dry appearance, interspersed with only occasional groves of *Eucalyptus globosus* and other exotic tree species. European seafarers in the 18th century (Forster, 1983 [1784]; Mureau, 1799) described Rapa Nui as a tree-

less landscape. The analysis of pollen, phytoliths, and macro-relicts delivered scientific evidence: thousands of years before people

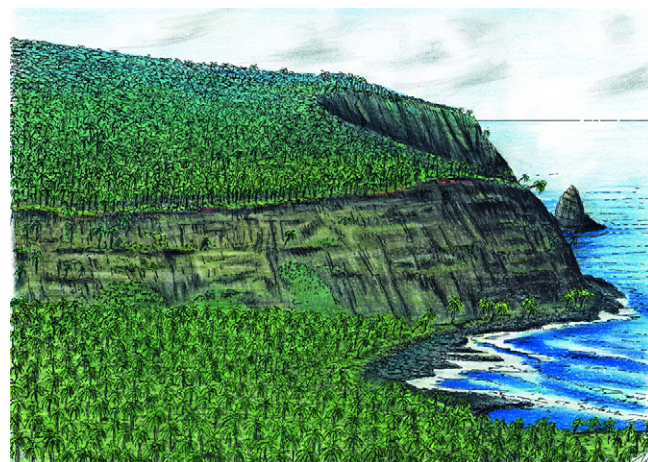


Fig. 1. A lost landscape: Rapa Nui was mostly covered with a palm-dominated woodland when humans first arrived. The palm trees and other woodland species are now extinct (illustration by courtesy of Wissenschaftliche Buchgesellschaft Darmstadt, in: Bork, 2006, p. 86).

* Corresponding author. Tel.: +49 0 431 880 4168 or +49 0 431 880 4030; fax: +49 0 431 880 4083.

E-mail address: amieth@ecology.uni-kiel.de (A. Mieth).

arrived at Rapa Nui, the island was covered with a highly diverse woodland (Fig. 1). The degradation began around 1000 AD and reached its height in the 17th century (Flenley, 1993; Orliac, 2000, 2003). Most indigenous and endemic plant species became extinct. One of these was a palm species, which once dominated the woodland and perhaps was endemic to Rapa Nui. Dransfield (in Zizka, 1991, pp. 65–66), classified the extinct palm Rapa Nui palm as a new genus/species (*Paschalococos disperta*). This classification was based on investigations by Dransfield et al. (1984) who described slight differences between the endocarp structure of the Rapa Nui palm and endocarps of *Jubaea chilensis*, a palm endemic to central Chile. However, the strong similarity between conserved seeds and phytoliths of the Rapa Nui palm and the related structures of *Jubaea chilensis* suggests that it was congeneric with *J. chilensis*, if not the same species (Delhon and Orliac, in press; Grau, 2005).

Jubaea chilensis is among the largest and longest living palm species on earth. Full-grown individuals easily become 15 m high and can occasionally grow up to 30 m. The life span of *Jubaea chilensis* is more than 300 years. The oldest trees in Chile have estimated ages of 750–1000 years (Grau, 2004, p. 87, p. 101; Hoffmann, 1998). The trees produce large amounts of seed in the form of miniature “coconuts”, ranging between 2 and 3 cm in diameter. It is highly plausible that the buoyant palm nuts invaded Rapa Nui as a result of ocean transport from the Chilean coast (Grau, 2004). Perhaps the palm on Rapa Nui underwent evolutionary speciation due to its isolation. New comparative analyses of the palm phytoliths now suggest more than one *Jubaea*-like species on Rapa Nui (Delhon and Orliac, in press). Here we term the Rapa Nui palm *Jubaea* sp., not defining the (one or more) species due to the current uncertainties.

2. Controversial discussion about the causes of Rapa Nui's deforestation

Who or what destroyed the ancient palm woodland on Rapa Nui? Several scholars assume that the prehistoric population of Rapa Nui was responsible for the deforestation. They argue that the Polynesian population grew quickly, that the people demanded open space for a growing number of dwellings and gardens, and that they demanded more and more firewood and timber (Diamond, 2005; Flenley and Bahn, 2003; Mann et al., 2003; Prebble and Dowe, 2008; Stevenson and Haoa, 1999; Van Tilburg, 1994). Trees are also thought to have been important for Rapa Nui's unique megalithic culture. Logs were possibly used for the transportation and erection of the giant stone statues (moai) and for the building of large stone platforms (ahu). There is consensus amongst most scholars that the Rapanui themselves had completed the deforestation of their island before the first Europeans arrived (Flenley, 1993; Flenley and Bahn, 2003; Flenley and King, 1984; Mieth and Bork, 2004; Rolett and Diamond, 2004).

The impact of climatic variations is also under debate. In sediment cores of Lake Rano Raraku, Mann et al. (2008, p. 24) found indications for a drought period “some time” between 3390 and 1180 cal yr BP. Despite this finding, the authors found in the sediment stratigraphy strong indications for significant human impact on the woodland in the form of rapidly increasing amounts of charcoal, an increase in mineral contents, and a decrease in palm pollen numbers, all beginning with the time of colonization. Nevertheless, the authors still do not rule out that an extreme weather period might have contributed to the woodland destruction. On the other hand, long-term pollen data from other investigations refute this idea. By way of sediment cores from the lake at Rano Raraku, Flenley and King (1984) documented the continuous presence of palm trees up to 35,000 years back in time, despite all climatic variations that happened or might have happened from the late Pleistocene until the late Holocene. This is supported by

Prebble and Dowe (2008, p. 2563) in their review paper on palm extinctions on numerous Pacific islands who see no indications for a palm extinction on Rapa Nui “following abrupt regional climate change events recorded from a range of proxies elsewhere in the Pacific”. Moreover, simulation experiments and climate modeling demonstrate that during prehistoric times neither El Niño events nor the “Little Ice Age” had significant effects on Rapa Nui's climate (Genz and Hunt, 2003; Junk, 2009; MacIntyre, 2001).

3. Rats or humans?

The discussion on the causes of Rapa Nui's deforestation was invigorated recently by the question of whether Pacific rats (*Rattus exulans*), not humans, might have destroyed the palm vegetation (Diamond, 2007; Flenley and Bahn, 2007; Hunt and Lipo, 2007).

The Pacific rat is the third most widely dispersed rat species on earth. This species was once a frequent companion on the sailing boats of the seafaring people in Oceania and colonized the islands of Melanesia, Micronesia and Polynesia together with the humans over time (Matisoo-Smith and Robins, 2004; Matisoo-Smith et al., 1998). More often than not, the seafarers deliberately transported the Pacific rats and set them ashore on the newly discovered islands since the rats represented a valuable source of protein, as did the domestic animals (especially chickens and pigs) that were also on the ships (Matisoo-Smith and Robins, 2004). During archaeological excavations, rat bones were commonly found in direct proximity of settlements, often in cooking pits (umu) and rubbish pits (Barnes et al., 2006; Martinsson-Wallin and Crockford, 2001; Mieth and Bork, 2004, pp. 80–81; Skjølsvold, 1994; Steadman et al., 1994). The fact of this specific coexistence between humans and rats on the one hand, and the modern DNA-analysis technology of rat bone relics on the other hand, enabled a detailed reconstruction of the spatiotemporal colonization in the southern Pacific (Matisoo-Smith and Robins, 2004).

However, it has not yet been determined when the first Pacific rats reached Rapa Nui and if they arrived with the first colonizers or possibly in the course of later arrivals of people. Last but not least, these questions are linked to recent debates about the chronology of human settlement on Rapa Nui, which are not the focal point here.

As mentioned earlier, based on radiocarbon data taken from the oldest occupation layer found at Anakena, and by the rejection of several older radiocarbon dates taken by other authors, Hunt and Lipo (2006) assume that Rapa Nui was not occupied before 1200 AD. However, our own findings concerning the development of land use mentioned below (relics of extensive horticulture in the palm woodland before 1200 AD, widespread and extreme labor-intensive woodland clearance as early as 1250 AD) are strong arguments in favor of colonization considerably before 1100 AD.

Rat bones that were found in the oldest occupation layers at Anakena have been dated to the following time frames: between 600 AD and 1260 AD (2 σ calibrated dates) according to Martinsson-Wallin and Crockford (2001, p. 246), between 800 AD and 1000 AD according to Skjølsvold (1994, p. 110), and between 1055 AD and 1400 AD (2 σ calibrated dates) according to Hunt and Lipo (2006, p. 1603). However, these dates have a limited spatiotemporal significance because it is not possible to deduce from these data that Anakena is the location of the first settlement on the island or that the first rats went ashore there. Furthermore, it is not yet possible, neither on the base of radiocarbon dates nor with help of genetic analysis of rat bones found on Rapa Nui, to tell if the Pacific rats actually arrived with the first colonizers or if they arrived at Rapa Nui with later arriving seafarers (Barnes et al. 2006, p. 1539).

Hunt (2006, 2007) does not only argue for a later settlement of Rapa Nui than is generally assumed by most scholars. He also sets up the hypothesis that the rat, which was imported by Polynesians, multiplied explosively on the island and destroyed the natural

woodland on Rapa Nui within a few centuries by consuming the palm seeds and/or other parts of the trees. He deduces his hypothesis from investigations by Athens et al. (2002) who reason a destructive behavior of *Rattus exulans* by palaeo-ecological investigations in the woodland on Hawaii.

Mann et al. (2008, p. 24) conducted investigations of sediment archives in the crater lake of volcano Rano Raraku which contradict this hypothesis. On the basis of pollen data they found no evidence for a significant impact of rats proceeding anthropogenic woodland destruction.

Brown (2006 [1924]) reported that rats were even valued as a currency by the Polynesian inhabitants in the past. This report indicates that rats were once not abundant, but rare on the island, and that people looked upon the animals as valuable (a food source) and not as a major environmental problem.

The following results of our investigations, based on the intensive analysis of soils and sediments at several sites, also disagree with the hypothesis of a major rat impact, and clearly support an anthropogenic interpretation for the demise of Rapa Nui's woodland.

4. Investigation strategy

We investigated the landscape development during the younger Holocene using landscape system analysis, which included the identification of natural and man-made structures and processes in excavated soils and sediments, detailed lab analysis of the physical, chemical and biological characteristics of soils and sediments, and radiocarbon dating of organic relicts. This approach results in a detailed spatial and temporal reconstruction of the landscape development of Rapa Nui, in which natural and anthropogenic effects can be separated. An important part of this methodology is the detailed investigation of anthropogenic remnants as well as soils and sediments in large exposures. On Rapa Nui, numerous exposures were opportunistically made available for study by soil erosion and, in one case (Maunga Orito, Fig. 2), by soil mining. The large extent of these profiles (cf. Fig. 2) enabled a reconstruction of the landscape development at several parts of the island.

5. Results

5.1. Remnants of the palm woodland

In many of the yellowish, brownish or reddish, loamy or clayey remnants of the primeval soils of Rapa Nui, we found traces of the ancient palm vegetation in the form of tube-like molds of palm roots



Fig. 2. Laterally extensive exposures provide windows into the prehistoric landscape. The photograph shows an extended exposure at Maunga Orito. The dark Holocene soil contains many root casts of the now extinct Rapa Nui palm.



Fig. 3. Casts of palm roots in the Holocene soil at Maunga Orito (illustration by courtesy of Wissenschaftliche Buchgesellschaft Darmstadt, in: Bork, 2006, p. 87).

(Fig. 3). These root tubes are 5–7 mm in diameter. Mann et al. (2003) also investigated the primeval soils with the palm root tubes on Poike peninsula. They mention that the root tubes occupy up to 40–50% of soil volume (Mann et al., 2003, p. 140). The root bundles of individual palms form cone-like patterns near the former soil surface and cylindrical patterns below (Fig. 5A (2) and Fig. 5B (2)). They are characteristically unbranched. In our investigations at Poike peninsula and in the surroundings of Rano Kau (for locations see Fig. 7) we often found root molds protruding more than 10 m into the weathered volcanic bedrock. The root casts can be easily seen in most exposures. The tubes are very solid due to hardening of the soil around them. At a few sites, remains of charred roots were found in the tubes, some of which have been dated (e.g. KIA, 18835, Table 1). Also, Mann et al. (2003, p. 140) mention that the root tubes contain traces of charred material. The well-preserved systems of root casts must represent the last generation of palms that grew on Rapa Nui since the overlap of root molds by more than one palm generation would have formed a mixture of root structures in the soils. Thus, something special in the life history of the last palm generation in each site must have caused the root printings. Root casts of two palm generations were found at one site only (at the inner slope in the western part of Rano Raraku, Figs. 7 and 14), which are represented in two layers, one above the other (see below).

The palm root casts have been described by some authors (Bahn and Flenley, 1992; Mann et al., 2003; Mieth et al., 2002). Mieth and



Fig. 4. Root mass of a living *Jubaea chilensis* palm in La Campana National Park, Chile. Note the cone shaped root formation and the unbranched nature of individual roots. The upper part of this root cone is exposed by soil erosion.

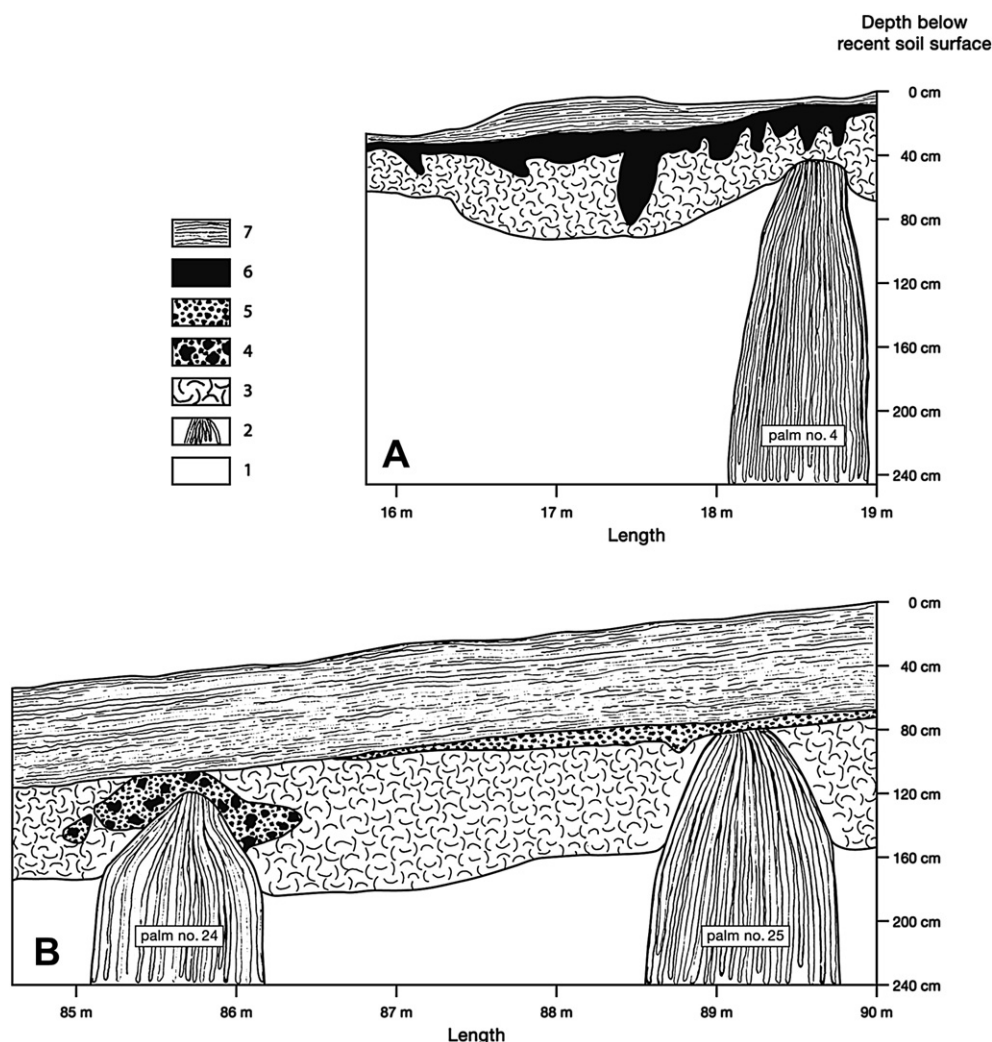


Fig. 5. (A,B) Two segments of a soil profile with a length of 100.5 m above the cliff in south west Poike. Location: S 27° 07' 21"/W 109° 16' 01". Summarized stratigraphy: (1) Weathered volcanic bedrock. (2) Cone of palm root molds. The soil between the root tubes has a consolidated structure which was caused by burning of the palm roots. (3) Pre-clearing garden soil. The loamy soil consists of small loose aggregates with a low bulk density due to ancient digging activity. Planting pits are very dense and overlap. (4) Accumulation of charcoal from a burned palm stump containing *in situ* aggregates of burned soil. Result of intentional burning by humans. (5) Charcoal layer. Charcoal layers are best preserved in concave down-slope sections. (6) Post-clearing garden soil with planting pits; the pit fillings are rich in organic matter and contain charcoal. Single planting pits are still visible due to a short period of land use during which the soil was not completely mixed. (7) Fine layered sediments, resulting from post-clearing sheet erosion of unprotected soil.

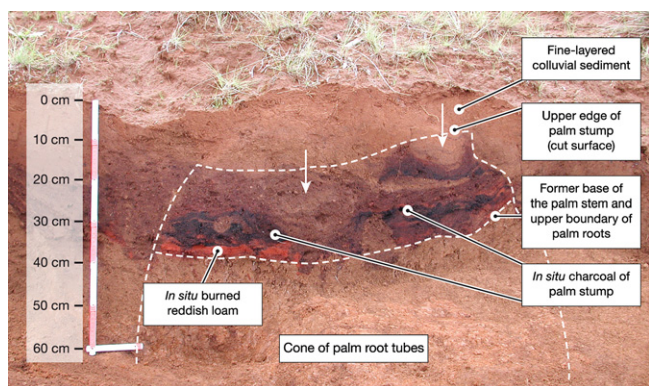


Fig. 6. *In situ* charcoal remains of palm stumps prove the slash and burn activities on Rapa Nui. The white arrows mark human disturbance (hollows filled with charcoal, soil aggregates and food remains). The glowing charcoal of this palm stump was obviously used for cooking.

Bork (2003) made the first systematic reconstruction of the spatial and temporal distribution of the last generation of palm woodland on the island. The cone-like root patterns of single palms (Figs. 4, 5 and 6) permitted the differentiation of individual palms, the determination of the spacing between palm trees, and the diameters of their root crowns. In this way, the authors reconstructed the stand structure of the prehistoric palm woodland, e.g. for a 100 m long soil profile in the south west of Poike peninsula (Mieth and Bork 2003, p. 73).

The reconstruction demonstrates that the palm woodland was very dense and that young palms grew between older and larger palms. Soil profiles with a cumulative length of more than 6,000 m scattered over the island show that about 70% of the island's surface was once covered by palm woodland. Only a few palm remains were found more than 250 m above sea level at Maunga Terevaka (Fig. 7). Mann et al. (2003) described the absence of palm root casts 300 m a.s.l. at the same volcano. Based on an average growing distance of 2.6 m between the trees and the documentation of more than 100 investigation sites referenced to an area of 117 km², we calculated that approximately 16

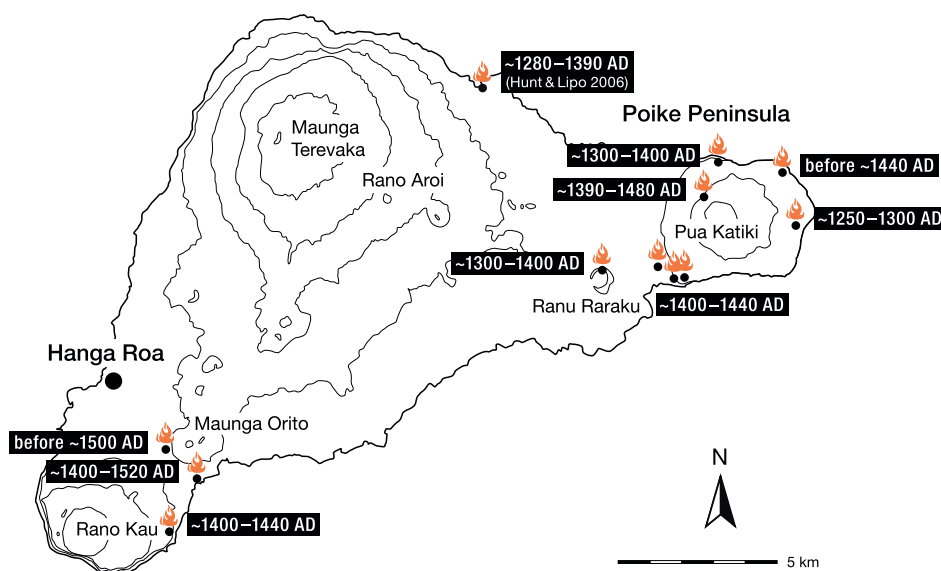


Fig. 7. The chronological sequence of slash and burn for 12 sites on Rapa Nui including a date from Hunt and Lipo's investigations in Anakena (Hunt and Lipo, 2006). Rounded data from calibrated radiocarbon dates in 2-sigma range. For details of data see Table 1 and Fig. 8.

million palm trees once grew on the island (Mieth and Bork, 2006). Thus, the palm trees dominated the ancient vegetation structure, both in terms of their large size (stem diameters up to 1.5 m) and their high density.

Certainly there were other trees and shrubs in the woodland. However, these left no root casts in the soil. Pollen findings and charcoal wood species identification prove the existence of a large

number of other species making up a mesophytic woodland vegetation (Flenley, 1993; Orliac, 2000, 2003; Orliac and Orliac, 2005).

Nevertheless, despite the diversity that once characterized the woodland of Rapa Nui, the *Jubaea* palm must have been a key species for the prehistoric human population. The palms must have been an enormous biotic resource for the early islanders,

Table 1

Radiocarbon data in context with woodland clearance from different locations on Rapa Nui.

Location	Type of sample	Sample code	Radiocarbon ages	Calibrated radiocarbon ages (2- σ range) ^a	Probability (%) ^b
Rano Kau (south)	Charred wood from burn layer	KIA 25977	BP 515 \pm 18	cal AD 1404–1436	95.4
Rano Kau (south near Vinapu)	Charred wood from burn layer	KIA 25976	BP 388 \pm 22	cal AD 1442–1519	78.2
Maunga Orito (south west)	Charred wood from planting pit	KIA 25975	BP 347 \pm 21	cal AD 1593–1622	17.2
Rano Raraku (West)	Charred wood from sediment	KIA 17569	BP 659 \pm 33	cal AD 1477–1531	35.3
Rano Raraku (west)	Charred wood from <i>in situ</i> palm stump	KIA 17119	BP 518 \pm 18	cal AD 1545–1635	60.1
Poike (east)	Charred palm nut from burn layer	KIA 17107	BP 731 \pm 25	cal AD 1283–1328	42.9
Poike (east)	Charred wood from post-clearance <i>umu</i>	KIA 18838	BP 588 \pm 22	cal AD 1344–1394	52.5
Poike (north)	Charred wood from burn layer	KIA 25778	BP 597 \pm 19	cal AD 1402–1436	95.4
Poike (south west)	Charred palm root from <i>in situ</i> palm root tube	KIA 18835	BP 951 \pm 32	cal AD 1244–1254	2.9
Poike (south west)	Charred wood from <i>in situ</i> palm stump	KIA 18836	BP 573 \pm 20	cal AD 1256–1299	92.5
Poike (south west)	Charred grass on palm stump	KIA 19369	BP 525 \pm 26	cal AD 1304–1367	68.7
Poike (south west)	Charred wood from post-clearance garden soil	KIA 18833	BP 482 \pm 26	cal AD 1384–1408	26.7
Poike (south west)	Charred wood from post-clearance sediment	KIA 19848	BP 529 \pm 24	cal AD 1303–1368	73.5
Poike (north west)	Charred wood from soil	KIA 18844	BP 498 \pm 45	cal AD 1383–1404	21.9
Poike (north east)	Charred wood from post-clearance <i>umu</i>	KIA 29457	BP 396 \pm 19	cal AD 1018–1162	95.4
				cal AD 1309–1356	55.3
				cal AD 1358–1365	1.9
				cal AD 1386–1416	38.2
				cal AD 1330–1341	8.6
				cal AD 1396–1438	86.8
				cal AD 1407–1448	95.4
				cal AD 1330–1342	9.5
				cal AD 1396–1437	85.9
				cal AD 1322–1351	9.5
				cal AD 1389–1480	85.9
				cal AD 1442–1510	88.7
				cal AD 1600–1613	6.7

Some data are published here for the first time, some data were published by Mieth and Bork (2003, 2004, 2006), Mieth et al. (2002) and Stevenson et al. (2006).

^a Transformation to calibrated ages with "CALIB rev 4.3, data set 2" after Stuiver et al. (1998).

^b The confidence interval of 2-sigma calibrated ages is 95.4% probability.

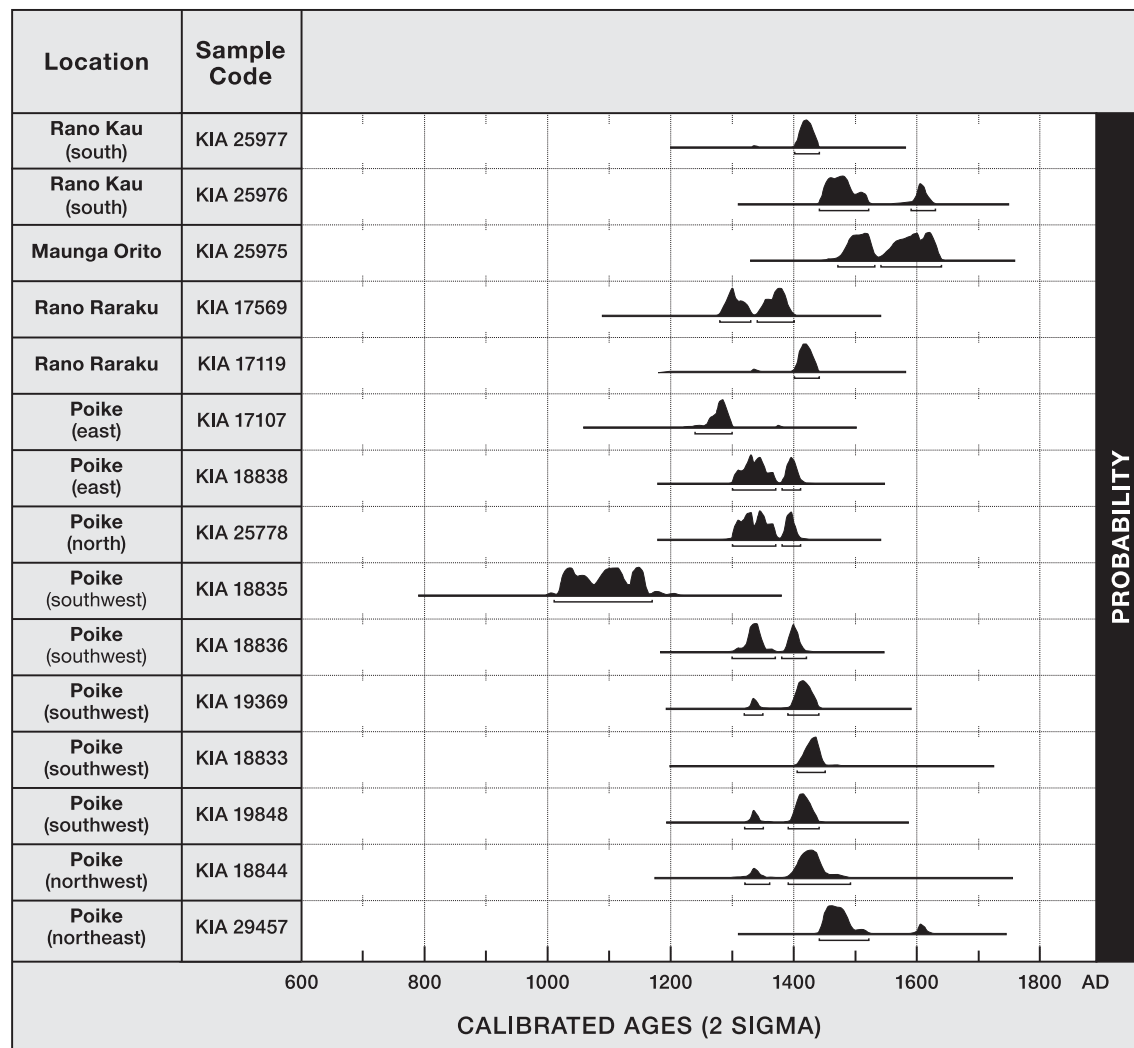


Fig. 8. Probability distributions for 15 calibrated radiocarbon dates (2-sigma) in context with woodland clearance from different locations on Rapa Nui. Calibration after Stuiver et al. (1998); curves generated with OxCal v3.10.

considering the implied abundance of stem wood, palm nuts, palm sap and palm leaves (Bork and Mieth, 2003; Grau, 1998; Orliac, 2003). Perhaps the *Jubaea* palm had the same value for the Rapanui as the coconut palm had for the inhabitants of other islands in Polynesia. Although coconut palms were imported and cultivated on many Pacific islands, they do not grow well on Rapa Nui because of its harsher climate.

The oldest cultural layers we found are garden soils that were integrated into the palm woodland. These garden soils are preserved between the undisturbed casts of the palm roots and underneath later cultural horizons (Fig. 5A (3) and Fig. 5B (3); Mieth and Bork, 2004, pp. 52–53 and p. 65, Fig. 35A). Thus, early crop cultivation was obviously an integrated part of the palm woodland with the advantage that the palms protected the gardens from drying, from harsh winds, runoff, and soil erosion by water and wind. Charcoal is very rare in the oldest cultural layers. Further investigations are needed to achieve more chronological details.

5.2. Evidence for slash and burn

Soil profiles in many areas of Rapa Nui provide evidence of fires in the former palm woodland. Over large areas, a single layer of

charcoal and ashes several millimeters in thickness can be found deep below the recent surface and on top of the prehistoric garden soils that belong to the period of woodland gardening (Fig. 5B). Occasionally we found several thin layers of charcoal on the lower and concave parts of some slopes. The explanation for this finding: the runoff of several intensive precipitation events evidently washed the charcoal downhill. The stratigraphic position of these charcoal layers above the level of the uppermost palm root casts is significant (Fig. 5B; Mieth et al., 2002, p. 91). The charcoal layers often contain burned nutshells of *Jubaea* palms and, in some areas, cover tens of thousands of square meters. For example, we found these extended burned layers on Poike Peninsula and in the south west of Rapa Nui. The extensive distribution of charcoal layers can only have one explanation: widespread fires in the woodland of Rapa Nui. Apart from an older age of a charred palm root (KIA 18835, Table 1), the oldest date of charcoal we obtained is from a burned nutshell from a soil profile in the east of the Poike Peninsula with a 2-sigma cal age of AD 1244–1254 and cal AD 1256–1299 (KIA 17107, Table 1). Thus, we interpret the 13th century to be the beginning of intensive slash and burn on Rapa Nui.

Numerous remains of burned palm stumps in the soils at several locations on the island (Fig. 6) support the hypothesis that the burning was caused by humans, not by natural events. Many palms

were cut efficiently a few centimeters above the soil surface. This is evident by clean cut, truncated surfaces of burned palm stumps which we found *in situ* at many sites on the island. Other parts of the palms (e.g. their leaves), and probably also parts of other trees and shrubs, were left on the surface and burned in large fires. We found charred plant remains of different macroscopic structures in the extensive burn layers around the palm stumps. The extraction of the very strong palm stumps was hard work for the people who cleared the land. Instead of pulling the stumps, they seem to have piled up dry plant material on top of them to increase their flammability. On some stumps we found carbonized stalks of grass which were used as fuel (Mieth and Bork, 2003, p. 74; KIA 19369, Table 1).

Another line of evidence supports that humans caused the burning. Some of the burned stumps show that they had been used as ovens for cooking. The charcoal layers in these stumps are disturbed by hollows caused by the placement and withdrawal of food that was obviously put into the glowing stumps (Fig. 6). Some hollows are filled with food remains, such as bone fragments, mixed with soil aggregates and charcoal pieces.

The clear differentiation of the root casts representing individual palm trees in the soils as well as charred remains of palm roots within the root tubes (KIA 18835, Table 1) suggest that large fires were responsible for the preservation and stabilization of the palm root casts. Perhaps a combination of pedo-chemical and pedo-physical processes with the direct heat impact on the soil plus physiological reactions of the roots to the burning led to the hardening, and thus to the stabilization, of the soil aggregates around the roots. By observation of recent forest fires, we noted that tree roots may burn over long distances and deep into the soil.

Fig. 7 summarizes the radiocarbon dating of the woodland clearance for 11 locations. Details of radiocarbon data are given in Fig. 8 and Table 1.

Clearance occurred in phases of deforestation on Poike peninsula between approximately 1250 and 1510 AD, and at the slopes of Rano Kao roughly between 1400 and 1520 AD. All data demonstrate that the destruction of the palm woodland on Rapa Nui probably lasted no longer than 300–400 years. This is supported by investigations of Mann et al. (2003, 2008) who sampled charcoal from the land clearing at the downhill slopes of Poike peninsula, on the slopes of Rano Kau, and at the volcano Maunga Terevaka. These authors leave no doubt that the abundance of charcoal above the primeval soils are the remains of widespread slash and burn (Mann et al., 2003, pp. 148–150; Mann et al., 2008, pp. 20, 24). Their radiocarbon data are consistent with our data, and testify that the main slash and burn activity occurred between 1200 AD and 1600 AD.

Whereas charred wood includes the problem of possible pre-dating of burning events, this is not the case for radiocarbon dates of charred palm endocarps which are short-lived parts of the palms. The ages of charred palm nuts, investigated by Delhon and Orliac (in press), Mann et al. (2008), Mieth and Bork (2003) and Orliac (2003) fall almost completely into the time frame between 1200 AD and 1450 AD. Dating inconsistencies between these investigations currently do not exist.

Both the temporal placement (after the onset of human colonization) and the sequential chronology of woodland clearance in different parts of the island underscore the conclusion that the deforestation was an act of humans. This is also underlined by the fact that man-made stone structures like *ahu* were established directly on top of the burned surfaces at many sites (Cauwe et al., 2006, pp. 99 ff; Mieth and Bork, 2003). At some locations we found evidence for horticulture established soon after burning/clearance (Fig. 5A (6); Mieth and Bork, 2003, Fig. 7; Mieth et al., 2002, Fig. 7; Stevenson et al., 2006).

5.3. Interactions between rats and palms

One indication for rats' influence on the palms might be rat teeth marks preserved in their seed shells (Mieth and Bork, 2004, p. 55). Dransfield et al. (1984, p. 750) and Hunt (2006, p. 217; 2007, p. 496) investigated endocarps of the extinct palm species and mention that all of the palm nuts have such gnaw marks. However, they inspected palm nut individuals that, with no exception, had been exposed and protected in caves for a long time. Therefore rats had a high chance to find and to eat them. Thus, it is not surprising that all nuts hidden in caves show bite marks. We mainly investigated charred endocarps (Fig. 9) that we found *in situ*, i.e. in the charcoal layers, and that had had a much shorter "life" span. Among more than 200 completely preserved and charred nutshells that we discovered in the burned layers, namely on Poike peninsula, less than 10% had the teeth marks of rats. This finding is supported by Vogt (2009, p. 16) who recovered numerous palm nuts that were un-charred and had been conserved exceptionally well under clayey sediments. Only a few had traces of gnawing.

For a comparative evaluation of the potential impact of rats on *Jubaea*-like palms, we searched for the impacts of rodents in the only place on earth where there is a large number of naturally occurring *Jubaea chilensis* palms. This is La Campana National Park in central Chile where there are about 80,000 palms (Grau, 2004, p. 49).

The *Jubaea* palms at La Campana are undergoing natural regeneration and include a wide range of different sizes and ages, including large numbers of young palms (Fig. 10). The palms have no obvious difficulty in reproducing and growing, and palm seeds clearly germinate (Fig. 11). The ground in this palm woodland is littered with thousands of palm nutshells (Fig. 12). We found many of these nutshells opened by small rodents with the pulp removed. These nutshells have gnawing marks at the edges of the nut openings – the same kind of teeth marks occurring on a few nutshells on Rapa Nui (Figs. 13 and 14). Grau (1996) mentions two species of mountain rats that inhabit La Campana: *Abrocoma benetti murrayi* and *Otodon degus*. He reports that both species pierce the



Fig. 9. A selection of charred palm nuts from the charcoal layers in the soil profiles of Rapa Nui. Most nutshells are completely preserved in the burn layers. They break easily during extraction due to their high fragility. Most charred palm nuts from Rapa Nui have no rat teeth marks.



Fig. 10. *Jubaea chilensis* woodland at La Campana National Park, central Chile, with diverse size and age structure of the palms (illustration by courtesy of Wissenschaftliche Buchgesellschaft Darmstadt, in: Bork, 2006, p. 88).



Fig. 12. Palm nuts of *Jubaea chilensis* cover the ground in La Campana National Park. Most nutshells have teeth marks from small rodents (e.g. mice, rats).

coconuts, break the woody endocarp, and eat from the endosperm. In spite of this significant rodent predation which is obviously much more extensive at La Campana than ever was the case on Rapa Nui (illustrated there by a high percentage of ungnawed nuts), the *Jubaea* palms at La Campana are able to regenerate, grow and form a dense palm woodland.



Fig. 11. *Jubaea chilensis* seeds at La Campana germinate well, despite the presence of rodents (photo: Juan Grau, in: Grau, 2004, p. 59).



Fig. 13. Close-up of nutshells of *Jubaea chilensis* from La Campana with the teeth marks of small rodents.

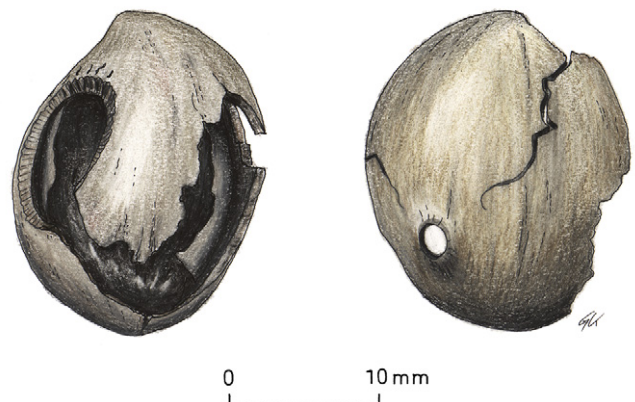


Fig. 14. For comparison: the (rare) teeth marks of *Rattus exulans* on a charred nutshell from Rapa Nui (illustration by courtesy of Wissenschaftliche Buchgesellschaft Darmstadt, in: Bork, 2006, p. 89).

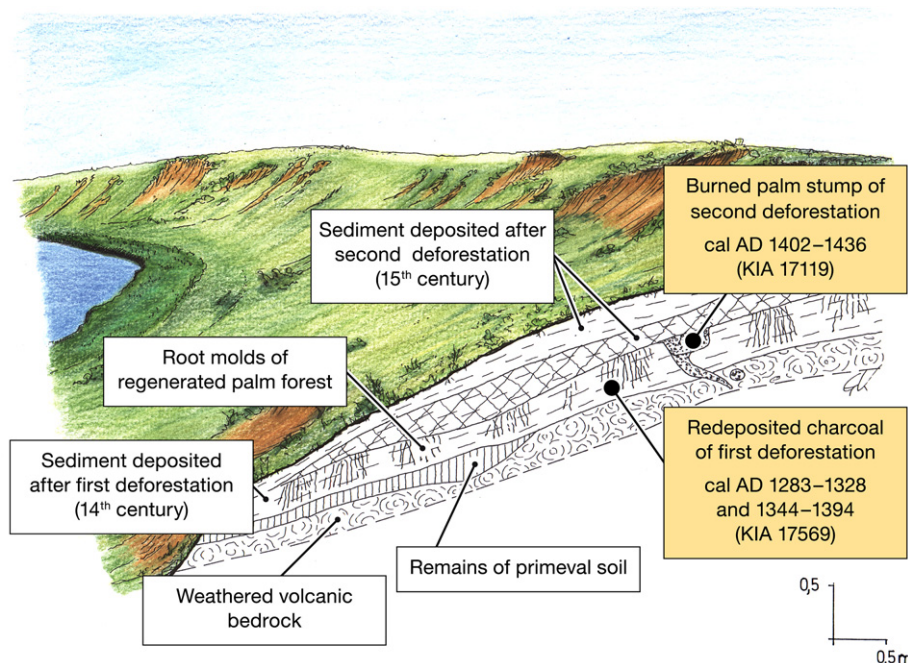


Fig. 15. The western interior rim of volcano Rano Raraku with rare evidence of palm regeneration after the first clearance. Location: S 27°07'11"/W 109°17'17".

5.4. An example of palm regeneration on Rapa Nui

The findings from La Campana prompt the following question: could the *Jubaea* palm woodland on Rapa Nui have been more sensitive to the presence of small rodents than the *Jubaea* palm woodland in central Chile, which has been exposed to rodents for thousands of years? To answer this question, we searched for evidence that would show whether palms on Rapa Nui were able to regenerate despite the presence of rats. We found proof of such palm regeneration in one area located on the inner slope of the Rano Raraku crater, northwest of the moai quarries. Exposures left by recent erosion enabled us to investigate and reconstruct landscape development in this area (Fig. 15). Embedded in a colluvial layer above the autochthonous soil, we found charcoal dating to the first deforestation at this site. This charcoal was dated to the late 13th and 14th centuries (2-sigma cal AD 1283–1328 and cal AD 1344–1394, KIA 17569, Table 1).

The overlying colluvial layer represents soil erosion and deposition after the first clearance of the palm woodland. Charred wood resulting from initial woodland clearance was mixed into the colluvium by the processes of erosion, transport, and sedimentation. Surprisingly, we found traces of a second, younger generation of palms within this colluvial layer in the form of palm root casts, as already described. Clearly, palms were able to regenerate after the primeval woodland was cleared from this site even though the woodland canopy had been opened, erosion had taken place, and rats were present on the island. Apparently, new palms regenerated for a while. These palms too were then cleared, again leaving charcoal behind, as in the remains of a burned palm stump, which we dated to the first half of the 15th century (2-sigma cal AD 1402–1436, KIA 17119, Table 1). Sediments then buried this younger level of palm root casts.

6. Conclusions: humans, not rats, were responsible for Rapa Nui's deforestation

Our investigations arrive at the definite conclusion that humans, and not rats or climate variations, destroyed Rapa Nui's palm woodland. This conclusion is based on the following findings:

- The degradation of palm regeneration by palm seed consuming rats has played at best a minor role. Less than 10% of the charred palm nuts carry teeth marks from rats.
- Rats cannot kill mature trees. Because of their long lifetime, palms that were fully grown in the 13th, 14th or 15th centuries could have survived until the first European contact time, if people had not cut them down.
- The relicts of palm stumps in many places demonstrate that these trees were felled by man. The palms were cut efficiently in large areas. Often, labor and material was invested to burn the stumps.
- Widespread ash and carbon layers show that fires burned over extensive areas.
- The root casts of the palms were preserved in the soil under the influence of fire and heat. Therefore, we could only find the roots casts of the last palm generation. We found two generations of palm trees cut and burned only at the western slope of Rano Raraku. The second palm generation grew there in a colluvial sediment resulting from water erosion after the first clearance.
- The diverse structure of the roots and stumps of the last palm woodland found in the soil profiles also proves the presence of young palms. Thus, young palm trees still existed some centuries after the introduction of rats and first deceased with the onset of clearing and burning.
- A section at Rano Raraku shows that palm trees were capable of regenerating after the initial woodland clearance. Also, this implies that rats were not able to prevent all palm regeneration.
- Pollen proxies in the lake sediments verify a long existence of the palm woodland on Rapa Nui before the appearance of humans and despite all climatic variations which occurred from the late Pleistocene to the late Holocene.
- Charred remains of short-lived parts of the palms like endocarps, dated between 1200 AD and 1450 AD, support the conclusion that the people felled living trees and not trees that were already dead (e.g. caused by a major drought period which might have occurred before colonization). Un-charred endocarps from dead trees would normally have been decomposed within a few years or decades and would not have

been available in such great numbers for burning events that happened centuries (or even millennia) after an assumed drought and decease of palms.

- The chronological sequence of fire events on Rapa Nui over some centuries and the introduction of new land use systems that took place immediately after the fire events underscore human intent and thoroughness in the elimination of the palm woodland.
- Small healthy populations of *Jubaea* palms coexist with populations of seed-eating rodents in central Chile and show the successful adaptation of the palms to pressure by animal consumption.

Acknowledgements

We could not have done our research on Rapa Nui without the manifold support of the local people. Our special thanks go to the Gobernador de Rapa Nui, to the Consejo de Monumentos Rapa Nui and to the Corporación Nacional Forestal (CONAF) for research permission and support for our field work. Our work benefited greatly from continuous discussions and exchanges with Christopher Stevenson, Jared Diamond, Georgia Lee, John Flenley, Juan Grau, José Miguel Ramírez and many others. Last but not least, we thank Piet Grootes and his team of the Leibniz Laboratory, University of Kiel, who carried out the radiocarbon dating. Last but not least we thank Candance Music and Nicole Bilsley for their support in translations and corrections of the manuscript.

References

- Athens, J.S., Tuggle, H.D., Ward, J.V., Welch, D.J., 2002. Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai'i. *Archaeology in Oceania* 37, 57–78.
- Bahn, P., Flenley, J.R., 1992. *Easter Island. Earth Island*. Thames and Hudson, London.
- Barnes, S.S., Matisoo-Smith, E., Hunt, T.L., 2006. Ancient DNA of the Pacific rat (*Rattus exulans*) from Rapa Nui (Easter Island). *Journal of Archaeological Science* 33, 1536–1540.
- Bork, H.-R., Mieth, A., 2003. The key role of *Jubaea* palm trees in the history of Rapa Nui: a provocative interpretation. *Rapa Nui Journal* 17 (2), 119–122.
- Brown, M.J., 2006 [1924]. *The Riddle of the Pacific*. Rapa Nui Press, Father Sebastian Englert Anthropological Museum, Easter Island – Rapa Nui, Hanga Roa.
- Bork, H.-R., 2006. *Landschaften der Erde unter dem Einfluss des Menschen*. Wissenschaftliche Buchgesellschaft, Darmstadt.
- Cauwe, N., Huyge, D., De Meulemeester, J., De Dapper, M., Claes, W., Coupé, D., De Poorter, A., 2006. Ahu Motu Toremo Hiva. Vie et mort de monuments cultuels sur l'île de Pâques. *Anthropologica et Præhistorica* 117, 89–114.
- Delhon, C., Orliac, C., in press. The vanished palm trees on Easter Island: new radiocarbon and phytolith data in: McLaughlin, S. (Ed.), *The Gotland Papers: Proceedings of the VII International Conference on Easter Island and the Pacific*. Easter Island Foundation, Los Osos.
- Diamond, J., 2005. *Collapse. How Societies Choose to Fail or Succeed*. Viking, New York.
- Diamond, J., 2007. Easter Island revisited. *Science* 317, 1692–1694.
- Dransfield, J., Flenley, J.R., King, S.M., Harkness, D.D., Rapu, S., 1984. A recently extinct palm from Easter Island. *Nature* 312, 750–752.
- Flenley, J.R., 1993. The palaeoecology of Easter Island, and its ecological disaster. In: Fisher, S.R. (Ed.), *Easter Island Studies. Contributions to the History of Rapa Nui in Memory of William T. Mulloy*. Oxbow Monograph 32. Oxbow Books, Oxford, pp. 27–45.
- Flenley, J.R., Bahn, P., 2003. *The Enigmas of Easter Island*. University Press, Oxford.
- Flenley, J.R., Bahn, P., 2007. Conflicting views of Easter Island. *Rapa Nui Journal* 21 (1), 11–13.
- Flenley, J.R., King, S.M., 1984. Late Quaternary pollen records from Easter Island. *Nature* 307, 47–50.
- Forster, G., 1983. [1784] *Reise um die Welt*. Inselverlag, Frankfurt am Main.
- Genz, J., Hunt, T.L., 2003. El Niño/Southern Oscillation and Rapa Nui prehistory. *Rapa Nui Journal* 17 (1), 7–14.
- Grau, J., 1996. *Jubaea*, the palm of Chile and Easter Island. *Rapa Nui Journal* 10 (2), 37–43.
- Grau, J., 1998. The *Jubaea* palm, key in the transportation of moai on Easter Island, in: Stevenson, C.M., Lee, G., Morin, F.J. (Eds.), *Easter Island in Pacific Context*. South Seas Symposium. Proceedings of the 4th international conference on Easter Island and East Polynesia. Easter Island Foundation, Los Osos, pp. 120–124.
- Grau, J., 2004. *Palmeras de Chile*. Ediciones Oikos, Santiago de Chile.
- Grau, J., 2005. Prehistoric presence of the Chilean palm in Easter Island, in: Stevenson, C.M., Ramírez, J.M., Morin, F.J., Barbacci, N. (Eds.), *The Reñaca Papers. VI International Conference on Rapa Nui and the Pacific*. Easter Island Foundation, Los Osos, pp. 29–34.
- Hoffmann, J.A., 1998. *Flora silvestre de Chile. Zona central*, 4th ed. Ediciones Fundación Claudio Gay, Santiago de Chile.
- Hunt, T.L., 2006. Rethinking the fall of Easter Island. New evidence points to an alternative explanation for a civilization's collapse. *American Scientist* 94 (5), 412–419.
- Hunt, T.L., 2007. Rethinking Easter Island's ecological catastrophe. *Journal of Archaeological Science* 34, 485–502.
- Hunt, T.L., Lipo, C.P., 2006. Late Colonization of Easter Island. *Science* 311, 1603–1606 (with supporting online material <http://www.sciencemag.org/cgi/content/full/1121879/DC1>, 17 March 2006).
- Hunt, T.L., Lipo, C.P., 2007. Chronology, deforestation, and "collapse": Evidence vs. faith in Rapa Nui prehistory. *Rapa Nui Journal* 21 (2), 85–97.
- Junk, C., 2009. *Einfluss klimatischer Effekte auf die Vegetation der Osterinsel*. Bachelor thesis in meteorology, Universität Hamburg, Fachbereich Geowissenschaften, unpublished.
- MacIntyre, F., 2001. ENSO, climate variability, and the Rapanui. Part II: Oceanography and Rapa Nui. *Rapa Nui Journal* 15 (2), 83–94.
- Mann, D., Chase, J., Edwards, J., Beck, W., Reanier, R., Mass, M., 2003. Prehistoric Destruction of the primeval soils and vegetation of Rapa Nui (Isla de Pascua, Easter Island). In: Loret, J., Tanacredi, J.T. (Eds.), *Easter Island, Scientific Exploration into the World's Environmental Problems in Microcosm*. Kluwer Academic/Plenum Publishers, New York, pp. 133–153.
- 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.
- Martinsson-Wallin, H., 2004. Archaeological excavation at Vinapu (Rapa Nui). *Rapa Nui Journal* 18 (1), 7–9.
- Martinsson-Wallin, H., Crockford, S.J., 2001. Early settlement of Rapa Nui (Easter Island). *Asian Perspectives* 40 (2), 244–278.
- Matisoo-Smith, E., Robins, J.H., 2004. Origins and dispersals of Pacific peoples: Evidence from mtDNA phylogenies of the Pacific rat. *Proceedings of the National Academy of Sciences of the United States of America* 101 (24), 9167–9172.
- Matisoo-Smith, E., Roberts, R.M., Irwin, G.J., Allen, J.S., Penny, D., Lambert, D.M., 1998. Patterns of prehistoric human mobility in Polynesia indicated by mtDNA from the Pacific rat. *Proceedings of the National Academy of Sciences of the United States of America* 95, 15145–15150.
- Mieth, A., Bork, H.-R., 2003. Diminution and degradation of environmental resources by prehistoric land use on Poike peninsula, Easter Island (Rapa Nui). *Rapa Nui Journal* 17 (1), 34–41.
- Mieth, A., Bork, H.-R., 2004. *Easter Island – Rapa Nui. Scientific Pathways to Secrets of the Past*. Schmidt und Klaunig, Kiel.
- Mieth, A., Bork, H.-R., 2006. The dynamics of soil, landscape and culture on Easter Island (Chile). In: McNeill, J.R., Winiwarter, V. (Eds.), *Soils and Societies. The White Horse Press, Isle of Harris*, pp. 273–321.
- Mieth, A., Bork, H.-R., Feeser, I., 2002. Prehistoric and recent land use effects on Poike peninsula, Easter Island (Rapa Nui). *Rapa Nui Journal* 16 (2), 89–95.
- Mureau, M. (Ed.), 1799. *La Perouse's Entdeckungreise in den Jahren 1785, 1786, 1787 und 1788. Erster Band. In der Possischen Buchhandlung*, Berlin.
- Orliac, C., 2000. The woody vegetation of Easter Island between the early 14th and the mid-17th centuries AD. In: Stevenson, C.M., Ayres, W.S. (Eds.), *Easter Island Archaeology. Research on early Rapa Nui culture*. Easter Island Foundation, Los Osos, pp. 211–220.
- Orliac, C., 2003. *Ligneaux et palmiers de l'île de Pâques du XIème au XVIIème siècle de notre ère*. In: Orliac, C. (Ed.), *Archéologie en océanie insulaire – peuplement, sociétés et paysages*. Éditions Artcom, Paris, pp. 184–199.
- Orliac, C., Orliac, M., 2005. *La flore disparue de l'île de Pâques. Les Nouvelles de l'Archéologie* 102 (4), 29–33.
- Prebble, M., Dowse, J.L., 2008. The late Quaternary decline and extinction of palms on oceanic Pacific islands. *Quaternary Science Reviews* 27, 2546–2567.
- Rolett, B., Diamond, J., 2004. Environmental predictors of pre-European deforestation on Pacific islands. *Nature* 431, 443–446.
- Skjølsvold, A., 1994. Archaeological investigations at Anakena, Easter Island, in: Skjølsvold, A. (Ed.), *Archaeological Investigations at Anakena, Easter Island. The Kon-Tiki Museum Occasional Papers, Vol. 3*. The Kon-Tiki Museum, Oslo, pp. 5–121.
- Steadman, D.W., Vargas Casanova, P., Cristino Ferrando, C., 1994. Stratigraphy, chronology, and cultural context of an early faunal assemblage from Easter Island. *Asian Perspectives* 33, 79–96.
- Stevenson, C.M., Haoa, S., 1999. Diminished agricultural productivity and the collapse of ranked society on Easter Island, in: Wallin, P. (Ed.), *Archaeology, Agriculture and Identity. No Barriers Seminar Papers (2)*. The Kon-Tiki Museum, Oslo, pp. 4–12.
- Stevenson, C.M., Jackson, T.L., Mieth, A., Bork, H.R., Ladefoged, T.N., 2006. Prehistoric and early historic agriculture at Maunga Orito, Easter Island (Rapa Nui), Chile. *Antiquity* 80, 919–936.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration 24,000–0 cal BP. *Radiocarbon* 40, 1041–1083.
- Van Tilburg, J.A., 1994. *Easter Island: Archaeology, Ecology and Culture*. British Museum Press, London.
- Vargas, P., Cristino, C., Izaurieta, R., 2006. *1000 Años en Rapa Nui: Arqueología del Asentamiento*. Universidad de Chile, Santiago.
- Vogt, B., 2009. *Wasserbau unterm Regenbogen*. *Archäologie in Deutschland* 4/2009, 12–16.
- Zizka, G., 1991. *Flowering Plants of Easter Island. Palmengarten*, Frankfurt am Main.