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SHORT COMMUNICATION

First records and potential palaeoecological significance of *Dianella* (Xanthorrhoeaceae), an extinct representative of the native flora of Rapa Nui (Easter Island)

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Abstract Easter Island, a remote island in the Pacific Ocean, is currently primarily covered by grasslands, but paleoecological studies have shown the former presence of different vegetation. Much of its original biota has been removed during the last two millennia, most likely by human activities, and little is known about the native flora. Macrofossil and pollen analyses of a sediment core from the Raraku crater lake have revealed the occurrence of a plant that is currently extinct from the island: *Dianella* cf. *intermedia/adenanthera* (Xanthorreaceae), which grew and disappeared at the Raraku site long before human arrival. The occurrence of *Dianella* within the Raraku sedimentary sequence (between 9.4 and 5.4 cal. kyr B.P.) could have been linked to the existence of favorable paleoenvironmental conditions (peatland rather than the present-day lacustrine environment) during the early to mid Holocene. This finding contributes new knowledge about indigenous plant diversity on Easter Island and reinforces the usefulness of further macrofossil and pollen analyses to identify native species on Easter Island and elsewhere.

Keywords *Dianella* · Easter Island · Native plant · Holocene · Palaeoecology · Local extinction

Introduction

Easter Island is a tiny isolated island in the South Pacific Ocean, famed as an example of environmental degradation due to human overexploitation of natural resources (Flenley and Bahn 2003; Diamond 2005; Rull et al. 2010a). Currently the island is covered nearly entirely by grasslands, but palaeoecological studies have suggested the occurrence of former forested vegetation dominated by palms and the presence of several other tree and shrub species (e.g. Flenley et al. 1991; Dumont et al. 1998; Azizi and Flenley 2008; Mann et al. 2008). Climatic changes and human activities during the last two millennia have largely modified the island's landscape and vegetation (Flenley et al. 1991; Flenley 1993a; Azizi and Flenley 2008; Mann et al. 2008; Butler and Flenley 2010; Cañellas-Boltà et al. 2013). A consequence has been the local extinction of a number of native species from the island. Among the most emblematic cases are the disappearance of the probably endemic palm *Paschalococos disperta*, a supposed close relative of the extant *Jubaea chilensis*, distributed throughout the coastland central areas of Chile, and the disappearance of *Sophora toromiro*, an endemic legume

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surviving only as a cultivated shrub on the island and in some botanical gardens elsewhere (Flenley et al. 1991; Zizka 1991; Maunder et al. 2000).

In addition to the disappearance of representatives of the original flora, numerous exotic species, such as *Eucalyptus* spp. and *Melinis minutiflora*, have been introduced in recent times, and some of these, such as *Psidium guajava* and *Crotalaria grahamiana*, have become invasive. Currently, the flora of Easter Island is composed of approximately 200 established vascular plant species (~180 flowering plants and ~17 ferns), of which 30 flowering species are considered native (Zizka 1991; Flenley 1993b). In a recent revision, Dubois et al. (2013) only recognized 36 native and extant vascular plants (including ferns). Among the many species that have been introduced, only ~15 are considered to have been brought by the original Polynesian settlers in the last millennia, while the rest are modern introductions occurring after European contact in the 18th century (Flenley et al. 1991; Flenley 1993b; Dubois et al. 2013). Moreover, most of the native plants are currently considered to be endangered due to human activities and are very scarce and restricted to particular habitats (Zizka 1991; Dubois et al. 2013).

Because of these striking vegetation changes, including local extinctions and introductions, occurring after human occupation, the native flora of the island remains poorly characterized. It has been speculated that the native flora could have been poor due to the small size and the extreme isolation of the island (Skottsberg 1956; Zizka 1991). Descriptions provided by some of the early European visitors to the island supply some information on the flora, but few collections were made and many of the descriptions were imprecise (Zizka 1991; Hunt 2007). This information has been complemented with archaeological studies of microfossils—pollen, phytoliths, and starch grains (e.g., Cummings 1998; Horrocks and Wozniak 2008)—as well as studies of macrofossils and wood charcoal (Orliac and Orliac 1998; Orliac 2000), which have provided more details on the flora following human settlement. However, direct evidence of the flora and its changes before human arrival is only provided by palaeoecological records, largely based on palynological surveys of lake sediment cores (e.g., Flenley et al. 1991; Azizi and Flenley 2008; Mann et al. 2008; Butler and Flenley 2010) and a few macrofossil records (Mann et al. 2008; Cañellas-Boltà et al. 2012). Here, we report the existence of a previously unobserved plant (*Dianella* sp.) that was part of the native Easter Island flora during the early to middle Holocene, long before human arrival, and which is now extinct. This species has been identified on the basis of its characteristic pollen and seeds, found in a sediment core from Lake Raraku. The ecological preferences and the potential palaeoecological usefulness of *Dianella* are discussed.

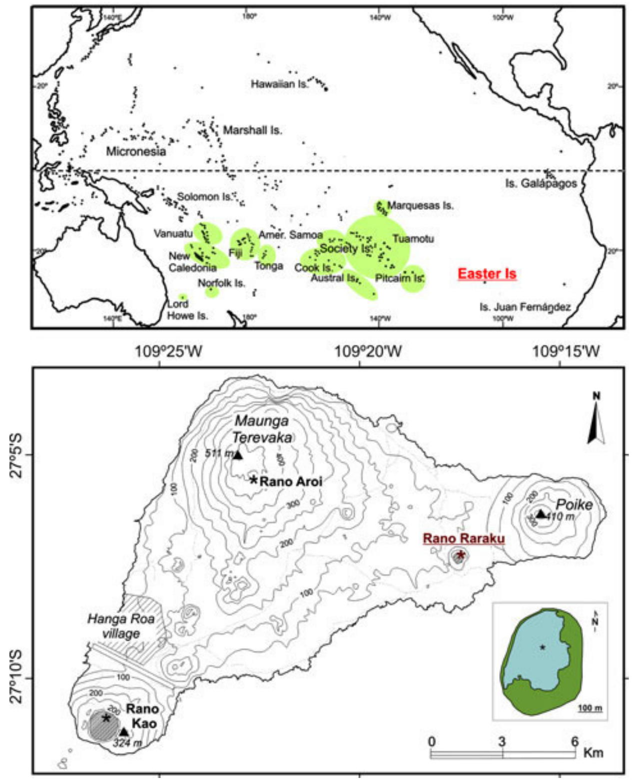

Fig. 1 *Above* map of current distribution of *Dianella intermedia*/*adenanthera* in the Pacific Islands (*shaded*) (see "Discussion" section for further information). Note that with the presence on Easter Island, the occupation area of the plant extended over practically all the tropical and subtropical fringe of the South Pacific Ocean. Map modified from Elix and McCarthy (2008). *Below* a map of the island showing the location of Lake Raraku (Rano Raraku). In the *box*, position of the coring point in the lake is shown

Study site

Easter Island is a subtropical volcanic island located in the South Pacific Ocean (27°7′S, 109°22′W; Fig. 1) approximately 3,700 km west of the Chilean coast and 2,030 km east of the nearest inhabited island (Pitcairn). The island has a roughly triangular shape, with three main volcanic cones, situated one in each corner, and an area of only ~164 km^2. The topography is characterized by the existence of these three main volcanoes, nearly 70 vents and the rolling surfaces of the lava flows between them. The highest point is the summit of the Terevaka volcano (511 m). No permanent surface streams are present because of the high permeability of volcanic rocks (Herrera and Custodio 2008). At present, only the bottoms of the craters of Rano Raraku and Rano Kau (now occupied by lakes), and Rano Aroi (now filled by a fen) permanently contain closed freshwater bodies. Currently, the island is mostly (90 %) covered by grasslands, with a few tree plantations, shrub areas and pioneer vegetation (Etienne

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et al. 1982). The climate is subtropical, with an average annual temperature of 21 °C and a range of average monthly temperatures between 16 and 18 °C (July–September) and 24–26 °C (January–March) (Mann et al. 2008; Sáez et al. 2009). The total annual precipitation is highly variable, ranging between 500 and 2,000 mm, with long alternating dry and humid periods (Horrocks and Wozniak 2008). The studied core was retrieved from Lake Raraku, a small (0.11 km^2) shallow (2–3 m deep) freshwater lake (Sáez et al. 2009), situated at an altitude of 75 m inside a volcanic crater more than 300,000 years old (Baker et al. 1974). The lake is topographically and hydrologically closed and disconnected from the island's main groundwater, and is fed solely by precipitation (Herrera and Custodio 2008). Today, the lake has a flat bottom and is surrounded by a littoral belt dominated by *Scirpus californicus*, which also forms large floating mat patches.

Materials and methods

This work is part of a palaeoecological study based on macrofossil and pollen analyses carried out on a sedimentary composite sequence 19 m in total length drilled in Lake Raraku. This sequence is mainly composed by peaty and lacustrine muddy sediments. The coring methods and a detailed stratigraphic description of the core are described in Sáez et al. (2009). Samples for the macrofossil analysis were processed following standard protocols (Birks 2001). A volume between 20 and 50 cm^3 of sediment per sample was analyzed. Dispersion of the sediment was facilitated by the addition of a small amount of KOH (10 %; more details are given in Cañellas-Boltà et al. 2012). Samples for pollen analysis were processed according to standard laboratory protocols for pollen analysis, slightly modified (Rull et al. 2010b), including KOH, HCl and HF digestions and acetolysis. *Lycopodium* tablets (batch 177745, Lund University, Sweden) were added to each sample before chemical processing as an exotic marker and used to calculate the pollen concentration. The microscopic pollen slides were mounted in silicone oil. The pollen and macrofossil data were plotted using psimpoll 4.26 (Bennett 2002). The chronological framework used in this work was established in previous studies based on radiocarbon dates on pollen-enriched extracts and *Scirpus* sp. fragments (Sáez et al. 2009; Cañellas-Boltà et al. 2012)

Results

Seeds and pollen of *Dianella* sp. (Fig. 2) dating from the early to mid Holocene have been identified in peaty sediments in the Raraku core (Fig. 3; Supplementary Data in ESM 1–3). The seeds were previously reported as unidentified macrofossils, using the code IBB-111 (Cañellas-Boltà et al. 2012). The pollen study of the sequence is still in progress. Both macrofossil and pollen records show the consistent presence of this taxon from ~7 to ~1.5 m downcore, with a continuous occurrence and greater abundance from 6 to 1.5 m (Fig. 3). According to the chronological framework established in previous studies (Sáez et al. 2009; Cañellas-Boltà et al. 2012), this corresponds to ~9.4–5.5 cal. kyr B.P., i.e., several thousand years before human occupation of the island. This plant has not been identified in previous palaeoecological and archaeological works, so this finding represents the first evidence of its presence on the island. The pollen assemblage corresponding to the interval with *Dianella* sp. is

Fig. 2 Seeds (**a**) and pollen (**b**) of *Dianella* sp. observed in Lake Raraku sediments. See more photographs in the ESM 2, 3

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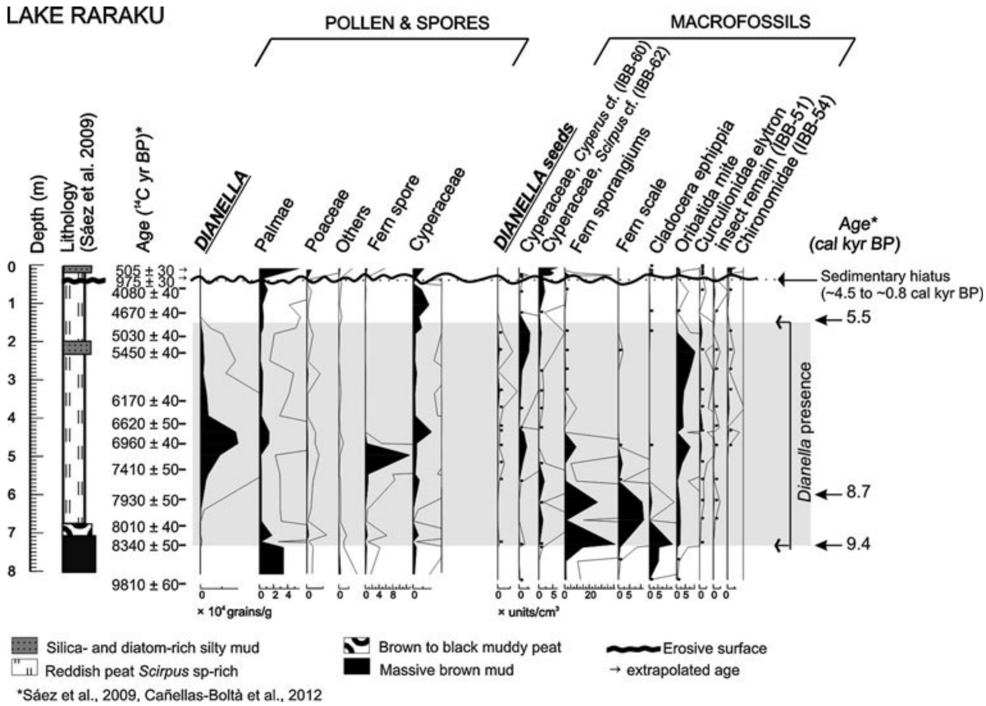

Fig. 3 Diagram of main pollen, spores and macrofossils in the first 8 m of depth of a core recovered from Lake Raraku, showing the presence of *Dianella* pollen and seeds at depths from 1.5 to 7 cm. Other includes pollen observed in very low concentration, such as *Sophora*, *Triumfetta*, Asteraceae and others. Lithology and ^{14}C radiocarbon dates are indicated on the *left*, and calibrated ages on the *right*. The period of time when *Dianella* is found is indicated in *shaded grey*

Fig. 4 Pictures of *Dianella intermedia/adenathera* (**a**, **b** from Norfolk Is. and **c** from Ravaivae). Photos by Matthew Prebble

characterized by the presence of palms, Cyperaceae, Poaceae and fern spores. The main macrofossils found together with the *Dianella* sp. seeds are Cyperaceae seeds and fern remains (sporangia and scales), and oribatid mites and insect fragments in great abundance (Coleoptera, Chironomidae, etc.) (Cañellas-Boltà et al. 2012).

Discussion

Taxonomic identity and biogeography

Dianella is a genus of evergreen rhizomatous herbs or subshrubs broadly known by the common name flax lilies (Fig. 4). As presently understood, *Dianella* is a monocot genus of flowering plants belonging to the Xanthorrhoeaceae, within the Asparagales, with 41 species recognized (Chase et al. 2009; APG III 2009; WCSP 2012). The genus is widely distributed in the Pacific Islands, from south-eastern Africa, through Southeast Asia to Hawaii, Australia, New Zealand and Bolivia (Moore and Edgar 1970; Smith 1979; Elliot and Jones 1984; George 1987, 1994; WCSP 2012) (Supplementary Data in ESM 4).

Both pollen and seeds of *Dianella* from the Raraku sediments are morphologically similar to *D. intermedia* and *D. adenanthera* (Fig. 5). The taxonomy of the genus is not fully resolved, and it is not yet clear whether these names are synonyms or correspond to two different species with

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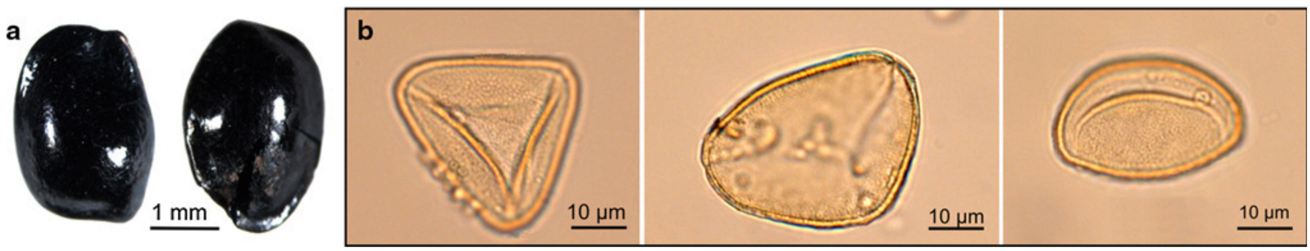

Fig. 5 Pictures of seeds (**a**) and pollen (**b**) of *Dianella intermedia/adenanthera*. Plant material from Allan Herbarium (CHR). Photos by Matthew Prebble

different distribution areas. For the purpose of this study, the name *D.* cf. *intermedia/adenanthera* was adopted. According to WCSP (2012), *D. intermedia* is endemic to the Norfolk Islands, whereas *D. adenanthera* is widely distributed in many of the Pacific Islands, such as Fiji, New Caledonia, Tonga, Vanuatu, and the Cook, Marquesas, Pitcairn, Society, Tuamotu, and Tubuai Islands (WCSP 2012) (ESM-4). This taxonomic and biogeographic distinction is not shared by other authors. The name *D. intermedia* has been used by some in a broader sense (George 1994) in the Pitcairn, Henderson, French Polynesian and other Pacific Islands (e.g., Smith 1979; George 1987; Paulay and Spencer 1989; Waldren et al. 1995; Florence et al. 2007; Franklin et al. 2008; Butaud 2010). A full revision of this genus is needed to clarify its taxonomy (George 1994).

However some differences in seed size and pollen morphology suggest that it might be another species, maybe an endemic plant. Nevertheless we do not have enough data to properly support this, and therefore we prefer to follow a conservative approach and have called it *D.* cf. *intermedia/adenanthera*. Another species of the genus present in the central and eastern Pacific Ocean is *D. sandwicensis*, which has a disjunct distribution that includes New Caledonia, the Marquesas Islands and the Hawaiian Islands (WCSP 2012). Nevertheless, its seeds are smaller and more obovate. Other current members of the genus (e.g., *D. carolinensis*, *D. saffordiana*) are located far from Easter Island, most of them with distributions restricted to certain islands, archipelagos or regions, although some others have wider distributions in the Pacific (e.g., *D. revoluta*, *D. ensifolia*, *D. javanica*) (ESM-4).

The results shown here, together with other past records from islands where the species is currently absent, such as Rimatara (French Polynesia) (Prebble and Wilmshurst 2009; Prebble, unpublished data), enhance the past distribution area of *D.* cf. *intermedia/adenanthera* across the Pacific.

Ecological preferences and potential paleoenvironmental usefulness

Extant *Dianella* species usually form dense terrestrial 1–2 m high clumps, tufts or spreading colonies that grow in many different habitats: grasslands, shrublands, moist forests, dry woodlands, grassy wetlands, coastal dunes, rocky areas, swamps and mires, etc. (e.g., Moore and Edgar 1970; Elliot and Jones 1984; Wardle 1991; George 1994; Hunter and Bell 2007; Franklin et al. 2008). Propagation can be by seeds, most probably through birds eating the fruit, but vegetative propagation by clump division is very common (Elliot and Jones 1984).

For the fossil *Dianella* recorded in this study, the lithological, geochemical and biological features of the sediments where its pollen and seeds were found can provide environmental insights into its habitat preferences. Although at present the bottom of the Raraku crater is occupied by a shallow lake, changes in the lake level and palaeoenvironment between lacustrine and mire conditions have been described since the Last Glacial Period (Sáez et al. 2009). The stratigraphic interval where *Dianella* is found in the Raraku sequence (~7 to ~1.5 m) corresponds to a sedimentary unit composed of reddish-brown massive and banded peaty deposits (Sáez et al. 2009). These deposits consist of abundant grass and sedge macroremains (notably sedge seeds), together with invertebrate faunal remains such as oribatid mites, Coleoptera Curculionidae and other animal fragments, which have been interpreted as indicative of mire conditions (Sáez et al. 2009; Cañellas-Boltà et al. 2012). The high concentration of *Dianella* pollen observed and the presence of numerous seeds suggest a highly localized and abundant presence of the plant, most likely growing directly on the palaeo-peatland inside the Raraku crater. Therefore, the results suggest that the pollen and seeds of *Dianella* in the record are associated with mire conditions (water saturated but not flooded), and hence, they are potentially useful as palaeoecological indicators of these conditions. This should be tested in further palaeoecological analysis. Although *Dianella* sp. are not species restricted to wetland habitats, some species have been observed in ombrotrophic bogs, swamps and other mires (e.g. Wardle 1991; Bell et al. 2012). These wetlands are characterized by being fed only by precipitation and by commonly being nutrient-poor and acidic, which may be similar to the past conditions of the Raraku palaeo-mire. Furthermore, macrofossil and pollen records suggest a plant community growing at that time in the crater dominated by *Dianella* sp. and Cyperaceae, with some Poaceae, as well as abundant ferns during the initial phases of this period (Fig. 3). The presence of palm pollen suggests the likely presence of palm stands surrounding the mire.

This palaeohabitat at the Raraku site would have been established after a lake level drop at the beginning of the Holocene (~9.4 cal. kyr B.P.) that transformed the late Pleistocene Raraku lake phase (characterized by muddy sedimentation) into a mire (Sáez et al. 2009). Both the progressive sedimentary infilling of the basin and possibly warmer and drier climate conditions would have favored the existence and development of such a mire environment during the early to mid Holocene period (Sáez et al. 2009; Cañellas-Boltà et al. 2012). Some palaeoclimatic records suggest that warmer and drier climatic conditions such as these occurred during the early to mid Holocene at similar latitudes along the west coast of central Chile (e.g., Jenny et al. 2002; Valero-Garcés et al. 2005; Maldonado and Villagrán 2006; Sáez et al. 2007; Kaiser et al. 2008). Previous palynological research on Easter Island has indicated that overall warm and moist conditions prevailed during this period (Flenley et al. 1991; Butler and Flenley 2010), although the possibility of some dry phases was also suggested (Flenley el al. 1991). However, a clear climatic scenario for this period cannot be drawn from these studies due to poor data, large sedimentary gaps, and the difficulty of establishing a sound chronological framework (Flenley et al. 1991; Flenley 1996).

Dianella extirpation at the Raraku site

Currently, *Dianella* is not found on Easter Island, either in natural or in cultivated form; therefore, it can be declared extirpated on the island. Climatic and ecological changes are the most likely causes for the growth and demise of *Dianella* sp. observed at Raraku. The disappearance of *Dianella* sp. from the pollen record coincides with an increase in Cyperaceae pollen (Fig. 3) and a shift in the Cyperaceae seed record, with the replacement of *Cyperus*-type seeds by *Scirpus*-type seeds (Fig. 3). Other noteworthy changes observed are the decrease in oribatid mite and insect remains and the appearance of some cladoceran ephippia (Fig. 3). These changes, combined with an increase in magnetic susceptibility (ms) and decreases in C/N and $\delta^{13}C$ values (Sáez et al. 2009; Cañellas-Boltà et al. 2012) suggest a likely progressive rise of the water level in the Raraku mire (Sáez et al. 2009), as has also been observed in similar records (Ancour et al. 1999; Hong et al. 2001). A high water table may have favored the development of more aquatic plants such as *Scirpus* sp. (which is now dominant in the lake littoral areas) and prevented the development of *Dianella* sp. and other plants typical of non-flooded habitats. This is consistent with some regional palaeoclimatic records of similar latitude in central Chile that suggest increased humidity approximately 5.7–4 cal. kyr B.P. (e.g., Jenny et al. 2002; Valero-Garcés et al. 2005; Maldonado and Villagrán 2006; Sáez et al. 2007; Kaiser et al. 2008), most likely as a result of an increase in the frequency of El Niño events (Kaiser et al. 2008).

The disappearance of *Dianella* from the Raraku record approximately 5.4 cal. kyr B.P. does not necessarily imply its coincident extinction from the island. Many *Dianella* species appear to be very resistant plants that can survive in extreme environments, growing in many habitats, including rocky outcrops and cliffs, as observed in populations from other Pacific islands. Moreover, the Raraku record does not capture the entire diversity of the island. Therefore, the continuity of *Dianella* in other Easter Island locations cannot be dismissed. Our data do not permit elucidation of the final decline of this plant on the island as a whole. Further palaeoecological research conducted on sediments from other localities, such as the Rano Aroi fen (Margalef et al. 2013) and the Rano Kau lake, will hopefully shed more light in this issue.

Conclusion and final remarks

The dramatic transformations of the landscape of Easter Island during the last millennia have resulted in numerous plant introductions and local extinctions. These changes, together with the lack of knowledge of the flora just before human arrival, as well as the few and imprecise reports of the first European expeditions, make it difficult to elucidate the native plant diversity on the island. Furthermore, determining whether a species is native or introduced (by Polynesian settlers or by the first Europeans or by the ensuing colonizers) is often complicated. This study provides an example of the usefulness of combined palynological and plant macrofossil studies of core sediments in identifying native plants and past plant distributions because such combined analyses provide unequivocal evidence of past plant occurrence. A new plant has been identified as native to Easter Island through the identification of seeds and pollen in sediments from a core recovered from a lake. This plant, *Dianella* sp., most likely *D.* cf. *intermedia/adenanthera*, was present during the early to mid Holocene (from 9.4 to 5.4 cal. kyr B.P.) in the Raraku crater in what was previously a peaty environment. Its presence in the sedimentary record of the Raraku basin infill is linked to the environmental conditions (mainly of the water table) that configured a mire environment in which the plant appeared to grow. Therefore, the presence of pollen and seeds of *Dianella* may represent potential palaeoecological indicators of such conditions. The

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disappearance of this plant is most likely linked to an increase in the water level in the Raraku crater but does not necessarily represent its total extinction from the island because the crater does not represent the complete diversity of the island. Studies such as this support the existence of greater diversity on the island than previously thought. Further palaeoecological research on sediments from other localities in Easter Island and other Pacific Island, would help to trace the history of *Dianella*.

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