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SHORT-LIVED PLANT MATERIALS, LONG-LIVED TREES, AND POLYNESIAN ^{14}C DATING: CONSIDERATIONS FOR ^{14}C SAMPLE SELECTION AND DOCUMENTATION

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ABSTRACT. For over 2 decades, there have been calls for Polynesian archaeologists to identify radiocarbon samples to taxon and material type, and preferentially date short-lived materials. This stems from recognition that even modest amounts of inbuilt age are problematic in this oceanic region where human settlement dates to the last 3 millennia or less. Despite programmatic statements to this effect, and empirical demonstrations of value, uptake of these practices has been slow. This article suggests that short-lived materials be defined as those with lifespans of 10 yr or less, recognizing that reducing the distance between target event and the dated material is an ongoing aim for archaeology. We identify both short-lived materials that are suitable for dating and long-lived species (>75 yr) that should be avoided given their potential for inbuilt age. Additionally, we suggest that given the destructive nature of ^{14}C dating there is value to (1) obtain high-resolution photographs of samples prior to analysis, (2) split samples and archive residuals when possible, and (3) routinely report the tools and expertise used in identification. Past and recent dating analyses at a Polynesian site in the southern Cook Islands are used to illustrate how the suggested protocols might enhance current and future studies. We also establish that mature *Calophyllum inophyllum*, a common coastal tree and valued timber species, has been in the southern Cook Islands for at least the last 700 yr and is likely to be indigenous and long-lived.

INTRODUCTION

Concerns about the accuracy and precision of radiocarbon sample measurements in relation to the timing of past cultural activities (the archaeological target events) are long standing, in the Pacific and elsewhere. The effects of inbuilt age in particular were recognized some 50 yr ago by Willard Libby, architect of the ^{14}C method. Arnold and Libby (1949) observed that long-lived trees may be problematic given that much of their girth can be dead wood that is considerably older than the near-surface tissues that underlie the outer bark, the locus of active growth. Archaeological texts and handbooks also routinely acknowledge the importance of using short-lived plant or animal materials (e.g. Bowman 1990:9; Loubser 2003; Maschner and Chippindale 2005:333; Renfrew and Bahn 2008:147–8; Hester et al. 2009:327; Kelley and Thomas 2009:147; Greene and Moore 2010:174). A quick review, however, shows that "short-lived" is usually not well defined and typically little guidance is provided with respect to material selection and documentation (but see Higham and Petchey 2000).

Inbuilt age in relation to ^{14}C dating is especially problematic in geographic locations where the time depth of human settlement is comparatively shallow, and materials suitable for relative dating are limited (e.g. ceramics, complex stone tools). East Polynesia is one such locality and the problem has been discussed in some detail (e.g. McFadgen 1982; Anderson 1991; Spriggs and Anderson 1993; Dye 2000; Allen and Wallace 2007; Wilmshurst et al. 2008; Della Casa 2009; Rieth et al. 2011). Archaeologists working in temperate New Zealand have been sensitive to the inbuilt age problem for some time, as many native New Zealand species can live for centuries and some are highly resistant to decay after felling (McFadgen 1982; Ahmed and Ogden 1987; Spriggs 1989; Anderson 1991; McFadgen et al. 1994). Arguments about the importance of using short-lived materials was extended to tropical East Polynesia by Spriggs and Anderson (1993:208) who identified "material of short lifespan" as a key factor among 17 criteria for accepting or rejecting any given ^{14}C determination. They also clearly established how long-lived materials could adversely affect understanding of key regional processes, especially island colonization. Despite this and subsequent reviews, archaeological practitioners have been slow to uptake such advice.

We suggest one problem has been uncertainty about the potential for significant inbuilt age in woody species from the tropical Pacific. Problematically, direct evidence for maximal tree lifes-

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pans is limited, although there are Pacific records of very large and probably quite old individuals (e.g. Figure 1; from Brown 1935). Direct dating of very mature individuals could help establish the longevity of different species, but these kinds of analyses have not been undertaken in the Pacific and are well outside the scope of most archaeological studies. Allen and Wallace (2007:1169, 1177) built a circumstantial case that tropical *Cordia subcordata* is a long-lived species and can have an inbuilt age on the order of 250 yr or more. Coupled with information from other tropical regions, where trees with lifespans in excess of 200 yr are common and maximal ages can be several hundred years (e.g. Ogden 1981; Lieberman et al. 1985; Worbes 2002), the possibility of long-lived species in the tropical Pacific warrants serious consideration.



Figure 1 A spectacular Marquesan (French Polynesia) example of *Cordia subcordata*, which exceeds most specimens found in the islands today where heights are more commonly around 7 m. Photo by Forest B H Brown, Bishop Museum, reproduced with permission from Bishop Museum (www.bishopmuseum.org).

Extended surface residence is a related problem, particularly in coastal settings where driftwood may accumulate on open ocean beaches. In the more eastern archipelagos of Polynesia, there also is the potential for very long-lived continental species to be represented. Redwood (*Sequoia* sp.), oak (*Quercus* sp.), pine (*Pinus* sp.), Douglas fir (*Pseudotsuga menziesii*), and Western red cedar (*Thuja plicata*) have been recovered from prehistoric Hawaiian wood charcoal assemblages, demonstrating that this is more than just a theoretical possibility (e.g. Murakami 1992; Dye 2000). Indeed, driftwood may account for some of the region's most anomalous early dates, as for example Suggs' (1961) 1st millennium AD results from Ha'atuatua Beach in the Marquesas Islands, determinations now considered well outside the time of human arrival (Allen 2004). The foregoing finds not only highlight the importance of identifying woody materials before dating, but also the value of photographic documentation before destructive analysis, archiving of sample residuals and, for undetermined but distinctive taxa, sufficiently detailed anatomical descriptions so that future identifications might be possible (see below).

Another oft-cited explanation for the slow uptake of Spriggs and Anderson's (1993) call to action is the lack of comparative collections or archaeobotanical expertise. Both, however, have been avail-

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able for over 2 decades as exemplified by several studies that draw on wood charcoal data for other purposes, including interpretations of past vegetation, fuel use, ritual activities, and other cultural practices (e.g. Murakami 1983; Wallace 1989; Kolb and Murakami 1994; Orliac and Orliac 1998; Allen and Murakami 1999; Lennstrom and Murakami 2003). In our view, a failure to fully appreciate the magnitude of potential inbuilt age in some tropical Polynesian trees, combined with ambiguity surrounding what constitutes "short-lived" materials, have been more important factors.

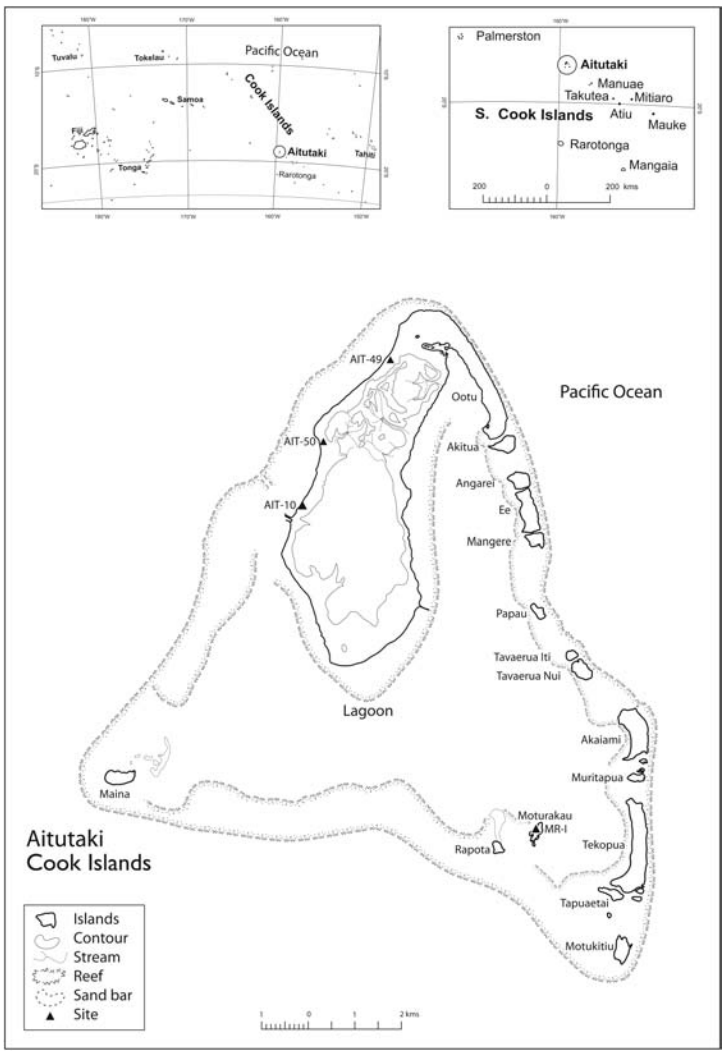


Figure 2 Map of Polynesia, the southern Cook Islands, and Aitutaki Island with key sites identified.

Given the foregoing, the objectives of this paper are to (1) provide a formal definition of "short-lived" in relation to ^{14}C dating, with the more general aim of reducing the chronological distance between the dated sample and the target event; (2) identify Pacific examples of useful short-lived materials and problematic long-lived species; and (3) suggest ways to improve sample documentation, recognizing that ^{14}C dating is a destructive process. Although sample accuracy can be evaluated post hoc, as for example by comparison with other ^{14}C results through formal Bayesian assessment, or by other dating methods (e.g. U-Th or relative dating), those approaches are not the focus of this study. Rather, the overall aim is to suggest ways to improve the process of sample selection and

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documentation, thereby enhancing the "shelf life" or long-term value of any given ^{14}C result. A case study from the Cook Islands (Figure 2) illustrates the potential value of these recommendations by comparing sample selection and documentation practices used 20 yr ago (Allen 1992, 1994) with those of a more recent study at the same site (Allen and Morrison 2013). Although the recommendations made here are for plant samples from Polynesia, the discussion is potentially useful for other material types and other regions.

IMPROVING SAMPLE SELECTION AND DOCUMENTATION PRACTICES

Assessing Inbuilt Age Potential

As described above, the importance of dating short-lived materials is widely acknowledged, but exactly what constitutes "short-lived" is not always clear. A number of years ago, McFadgen et al. (1994) provided a list of New Zealand plants of short (<100 yr), medium (100–300 yr), and long lifespans (>300 yr), with the assistance of botanist Phillip Simpson. Issues of inbuilt age also have been addressed by Anderson (1991) for New Zealand and Spriggs and Anderson (1993) for East Polynesia generally. Highlighting our evolving definition of what constitutes "short-lived," Anderson (1991) noted that "charcoal samples of 'short lifespan' species, even where the material also appears to be of young wood, still indicate inbuilt ages of 50–150 years," citing results from a New Zealand moa-hunting site. Rieth et al. (2011:2743) contrast Hawaiian taxa with lifespans of less than 50 yr with those of 50 yr or more, considering the former "short-lived," while Rieth and Athens (2013)[2] adopt a definition that is similar to what is promoted here. Some practitioners have categorized ^{14}C samples in relative terms (low, moderate, and high) with respect to the potential for inbuilt age (e.g. Anderson et al. 2003; Kirch et al. 2004; Kahn 2006), but while useful these terms are open to interpretation. Ambiguity in definition is not, however, unique to archaeological dating. Foresters often consider long-lived trees as those with multicentury lifespans (e.g. Pretzsch 2009:2–8), while ecologists sometimes identify lifespans of 30–70 yr as "short-lived" (e.g. Franklin 2003:680). Many botanical publications do not provide any formal definition.

Fast-maturing reproductive parts (fruits, nuts, and seeds), leaves, and twigs are ideal materials for ^{14}C dating, as all usually form within a few years, or less. Small-diameter branches also are sometimes considered "short-lived," but unless bark is retained on the outer surface, rays sharply converge, or pith is present, branch diameter can be difficult to determine with confidence on fragmented archaeological materials. Bark itself is sometimes assumed to be short-lived, but this is not necessarily the case as, while the inner bark of trees is the locus of living cells, much of the outer bark is comprised of nonliving tissue. Bark formation and growth can vary widely by species and environment, and the dead outer bark may stay with the tree for life, especially in tropical trees (Evert 2006:434). Stems from ferns, shrubs, and some monocots also may represent less than a decade of growth, but this is not universally the case. In short, when the material is not identified to taxon and "short-lived" is defined solely on the basis of specimen size or assumed state of maturity, considerable uncertainty is introduced, especially in the absence of supporting documentation.

The greatest concern for ^{14}C dating, however, is aged trunk wood. Problematically, the lifespans of many arborescent Pacific taxa are not well known, and contemporary mature individuals might not reflect the potential longevity of the species in question. Pauly (1995), dealing specifically with marine fisheries, cautions against "shifting baseline syndrome," wherein size parameters of populations

2. The present paper has had a long gestation period, dating from 2010 when samples from Moturakau Rockshelter were selected for AMS analysis at ANSTO. In the interim, Rieth and Athens (2013) have developed a more general paper with advice on sample selection and calibration that targets the Hawaiian archaeological community. That paper not only complements some of the ideas presented here, but their Table 1 indirectly suggests a similar definition for short-lived materials (~10/15 yr or less).

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from the recent past are used as a guide to conditions at earlier points in time; as a consequence, the baselines for comparison shift with each succeeding generation of scholars. Pacific island forests were highly modified by the region's first human settlers and very old trees were undoubtedly lost in this transformation, some making their way into prehistoric features and occupation debris. Nineteenth and early 20th century documents remind us of the extraordinary size (and presumably great age) achieved by some tropical Pacific species, as illustrated in Figure 1. Rock's (1913) discussion of Hawaiian sandalwood also highlights significant changes in native forests within the postcontact period. His early 20th century surveys identified sandalwood specimens that were at most 30 or 40 feet tall. In contrast, native informants told him that sandalwood trees once reached heights of 80 feet, with trunks often 3 feet in diameter. Introduced pests also have contributed to smaller tree sizes. Friday and Okano (in Elevitch 2006), for example, note that the growth rate and height of contemporary Hawaiian *Cordia subcordata* trees are stunted by an adventive leafworm.

A related problem is that neither growth rate nor successional role are necessarily reliable guides to maximal lifespan. Some long-lived species are fast growing and some pioneer species can live for decades (Franklin 2003:679–80). Suspect in this regard is *Hibiscus tiliaceus*, a fast-growing and often pioneer species that is commonly dated by Polynesian archaeologists. The taxon can, however, reach considerable size and its maximal lifespan is not known. Given the foregoing, we suggest the following definitions be adopted for ^{14}C dating:

1. Short-lived materials or taxa: lifespans of a decade or less;
2. Medium-lived materials or taxa: lifespans of between 10 and 75 yr;
3. Long-lived materials or taxa: lifespans in excess of 75 yr.

Given that the lifespans of most tropical trees are unknown, these age ranges are at best idealized guidelines, but they have the advantage of being explicit. We also suggest that the distinctions between decadal, multidecadal, and greater temporal scales ultimately relate to the target events archaeologists hope to understand (e.g. human life-history phases, generational-scale processes, and multigenerational societal changes), as well as the developmental times of particular plant parts and the variable lifespans of different species. While medium-lived plants at 10–75 yr are within 1 standard deviation of most contemporary ^{14}C results, this situation may change as ^{14}C technologies evolve; in the last 20 yr, for example, error ranges associated with conventional ^{14}C ages have halved and are now routinely around ±25 to 40 ^{14}C yr.

Table 1 is a list of potentially long-lived species found in Polynesia (excluding New Zealand), which builds on the tropical Pacific list of Allen and Wallace (2007) and includes some widely distributed taxa from Rieth et al.'s (2011) Hawaiian list. The lifespan information is based on individuals of known age, ^{14}C results, historical documents, and/or anecdotal accounts, admittedly less than ideal but presently our best sources of information. Unfortunately, determining maximal lifespans for tropical trees is quite challenging and the subject of some debate amongst botanists (Worbes 2002:221). The list provided here is not intended to be comprehensive but rather focuses on taxa that are likely to have been used as fuel species by prehistoric Pacific peoples, because of their ecological associations (e.g. lowland), relative abundance in native forests (i.e. common), burning properties (see Elevitch 2006; Huebert et al. 2010:86–90), or other attributes. The main purpose of Table 1 is to highlight taxa with the greatest potential for inbuilt age. Given that the amount of inbuilt age in any given ^{14}C sample cannot be known *a priori*, long-lived species (>75 yr) are best avoided in archaeological dating. Importantly, however, even charcoal specimens identified to a particular long-lived species can vary in the amount of inbuilt age, ranging from modest-to-negligible in juveniles to considerable in the case of heartwood from very old individuals. For this reason, in our

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view, charcoal offsets or correction factors should only be devised using large assemblages and in geographically restricted circumstances, as suggested by Bronk Ramsey (2009). Further, it may not be appropriate to compare such values across sites, especially without considering comparability of the local flora, island size, climate, and other factors that might affect tree longevity.

Table 1 Estimated maximal lifespans of long-lived (>75 yr) indigenous and Polynesian-introduced woody species that are commonly found in archaeological assemblages.

Name	Maximum recorded size[1]	Estimated maximal age[1]
Acacia koa[2]	Very large trees up to 35 m	Unknown; largest native Hawaiian tree
Aleurites moluccana	Large trees to 20 m, trunk to 110 cm	>70 yr
Alphitonia spp.	Very large trees to 30 m; trunk up to 1 m diameter	Unknown
Artocarpus altilis	Large trees to 25 m	Many decades
Barringtonia asiatica	Large trees to 20 m	80–90 yr
Calophyllum inophyllum	Large trees to 20 m	>70 yr (see text)
Cocos nucifera[3]	Very large woody monocot, up to 35–40 m	Up to 100 yr
Cordia subcordata	Large trees to 15 m; trunk to 100 cm diameter	>100 yr
Diospyros spp.	Tree to 12 m	Unknown, but slow growing
Erythrina spp.	Large trees to 20 m	Up to 100 yr
Ficus prolixa	Large trees to >30 m with wide network of prop roots	>100 yr
Inocarpus fagifer	Very large trees to 30 m	80–90 yr
Metrosideros spp.	Size varies widely from shrub to large tree >20 m	Many centuries
Myoporum sandwicense[2]	Shrubs to large trees, to 18 m; trunk to 100 cm diameter	Unknown
Neonauclea forsteri	Large trees to 25 m; trunk to 100 cm diameter	Unknown but may be long-lived based on size
Nestegis sandwicensis[2]	Large trees to 20 m; trunk to ~100 cm diameter	Unknown
Pandanus tectorius[3]	Large shrub or small tree, up to 15 m	Up to 100–150 yr
Planchonella spp.	Variable in size, up to 40 m; large tree with trunk to 70 cm diameter	Not known but may be long-lived based on size
Santalum spp.	Large trees to 40 m; trunk to 90 cm diameter	Unknown but historic accounts describe very large specimens before sandalwood boom (Rock 1913:131)
Sapindus spp.	Variable in size; up to 25 m in some Hawaiian environments	Unknown
Sophora chrysophylla[2]	Shrubs and trees to 12 m; trunk to 60 cm diameter	Unknown
Terminalia spp.	Large trees to 25–40 m	60–100 yr
Thespesia populnea	Trees to 20 m; trunk to 80 cm diameter	Many decades

[1]Data compiled primarily from Elevitch (2006), Butaud et al. (2008), and Rock (1913) with contributions from Allen and Wallace (2007), Krisnawati et al. (2011); McFadgen et al. (1994), and Rieth et al. (2011).
[2]Species listed are Hawaiian endemics but give insights into potential size and lifespan characteristics within these genera.
[3]Wood of large palms can be long-lived and is not ideal for dating (e.g. Delhon and Orliac 2008:100).

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Table 2 Short-lived Polynesian plant materials (lifespan 10 yr or less) that have been recovered archaeologically.

Scientific name	Common name	Material	Reference[1]
Aleurites moluccana	Candlenut	Endocarp or endosperm	Dye 2011; Field et al. 2011
Canarium spp.	Galip nut	Endocarp	Fairburn and Swadling 2005; Kirch 1989
Cocos nucifera	Coconut	Endocarp or husk	Allen and Wallace 2007; Petchey et al. 2009; this paper
Colocasia esculenta	Taro	Corm	No dated examples but occasionally recovered (e.g. Allen 1981)
Cordia subcordata	Kou, Tou	Fruit or seeds	Kirch 1989
Inocarpus fagifer	Tahitian chestnut	Pericarp	Kirch 1989
Ipomoea batatas	Sweet potato	Tuber	Coil and Kirch 2005; Dye 2011; Ladefoged et al. 2005
Lagenaria siceraria	Bottle gourd	Fruit or seeds	Dye 2011; see also Allen 1981
Pandanus spp.	Screwpine	Drupe	Di Piazza 1998, 1999; this paper
Saccharum sp.	Sugar cane	Stem or leaves	No dated examples but occasionally recovered (e.g. Allen 1981)
Spondias dulcis	Vi apple	Endocarp	Kirch 1989
Terminalia spp.	Tropical almond	Seed	Kirch 1989

[1]These citations include site-specific findings where the reliability of results from these short-lived taxa are either directly considered or demonstrated through paired samples and/or relationships to a larger series of determinations.

Table 2, in contrast, identifies short-lived plant materials that are relatively common in Pacific archaeological sites and have provided acceptable ^{14}C results in the past (e.g. through paired samples, or those that are consistent with other samples in a stratigraphic series). In many cases, these materials also are morphologically distinctive, in particular the fruits of *Aleurites moluccana*, *Cocos nucifera*, *Canarium*, *Pandanus*, and *Terminalia*. With respect to the dating of initial human occupation, *Aleurites* has the added benefit of being a Polynesian introduction, and thus unambiguously associated with human arrival. *Pandanus*, while indigenous to most Polynesian islands, was a food for humans and also frequently (and distinctively) gnawed by the anthropogenically dispersed Polynesian rat (*Rattus exulans*) (Prebble and Wilmshurst 2009). Occasionally, ^{14}C samples are comprised of materials that are unidentified with respect to taxon but are demonstrably short-lived based on some other criteria. For example, twigs or grass stems might not be identifiable to species or genus but generally qualify as short-lived. To insure confidence in the associated ^{14}C results, we suggest that the attributes of these kinds of materials be described and photographically documented (see below) rather than simply claimed.

Although the foregoing discussion focuses on plant materials, similar considerations apply to animal remains. The average and maximal lifespans of many vertebrates and invertebrates are not well known and may vary with local environmental conditions (e.g. Powell and Cummins 1985). Mature individuals are likely to be disproportionately represented in archaeological sites from the earliest periods of island settlement. Systematic treatment of suitable faunal materials in relation to ^{14}C dating is beyond this paper, but Petchey and colleagues review related issues elsewhere (Petchey 2000, 2009; Petchey and Higham 2005; Petchey et al. 2008, 2013; Petchey and Clark 2011).

Some additional considerations are worth noting. Even short-lived materials can have extended surface residence times, depending on their chemical composition, anatomical structure, and preservation context (McFadgen 1982). Also, medium- or long-lived taxa may be represented by short-lived woody materials, as for example, juvenile individuals, twigs, or small branch wood, and should

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not be dismissed out of hand (see Wallace and Green 2012); the greatest potential for sampling of mature individuals undoubtedly lies in early settlement sites. Finally, while long-lived materials are generally to be avoided and short-lived materials are recommended, many analysts often utilize materials that fall in the intermediate category, probably by necessity rather than choice (see Kirch et al. 2004:95), and in some cases the results may be adequate for the research questions of interest. For example, in Hawai'i several woody shrub species, probably with moderate inbuilt age at the most, have been used for dating with apparently reliable results, including *Euphorbia* (formerly *Chamaesyce*), *Chenopodium*, and *Sida* (Coil 2004; Dye 2000; Field et al. 2011; Rieth et al. 2011).

Reference Collections and Specialists

Reference collections lie at the heart of all bioarchaeological identification work and the quality of these collections directly affects the quality of taxonomic determinations. Although identifications are often undertaken by specialists, archaeologists relying on those services might consider the following in using the results provided.

Adequate taxonomic coverage is a key consideration for any reference collection and in much of the tropical Pacific high biodiversity, coupled with the abundance of speciose taxonomic groups, make this a particular challenge. Multiple specimens from varied locations are often needed as species may exhibit considerable ecological or geographic variability (e.g. Fisher et al. 2007; Fichtler and Worbes 2012; Sastrapradja and Lamoureux 1969). For wood reference collections in particular, it is useful to have both charred and uncharred specimens, and all reference collections benefit from the inclusion of juvenile materials.

While detailed reporting of the reference collections used in ^{14}C sample identifications is generally not feasible, basic information on the size, geographic coverage, and repository of the comparative materials should be routine, given how important sample identity has become to the accepted validity of dating results and archaeological interpretations. Several specialists have published details of their reference collections (e.g. Coil 2004:327; Prebble et al. 2012:183), and consumers of identification results might usefully cite these sources. Although no attempt is made here to evaluate the impact, it is noteworthy that the reference collection used by Murakami in the early 1990s to identify Allen's Aitutaki wood charcoal for vegetation reconstructions (Appendix A in Allen 1992) contained only 156 specimens, while that used by JMH in the more recent chronometric analysis included 350 specimens, a nearly three-fold increase in reference taxa that potentially facilitated new taxonomic identifications.

Lastly, there is value in identifying the person responsible for bioarchaeological identifications and the resources they used in arriving at those conclusions, regardless of whether or not a specialist was involved. Notably, this is already a requirement of reporting in *Radiocarbon*, but not a routine practice elsewhere. These individuals may retain sample residues, photographs, or laboratory notes that might be of use in future analyses.

Sample Documentation

Given the destructive nature of ^{14}C dating, there are several advantages to obtaining high-resolution photographs of identified materials prior to laboratory submission. This is easily achievable with accelerator mass spectrometry (AMS) samples, which often consist of single fragments (e.g. Anderson et al. 2003; Fairburn and Swadling 2005), but even with large wood charcoal assemblages, photographic documentation of representative specimens of specific taxa would aid future studies. High-quality photographs, including close-ups of distinctive features, would be especially helpful to future assessments if a portion of the sample cannot be archived.

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As an example of a photographic system, the University of Auckland wood charcoal laboratory uses a Zeiss Axio Imager epi-illuminated microscope with magnifications of 50–500×, AxioVision software, and a digital camera. The three planes used in identification work (transverse, radial, and tangential longitudinal sections) are easily photographed and the setup allows for close-up photos of diagnostic anatomical features. Materials like charred nut shells, where surface textures and shapes can be crucial for identification, are typically photographed at lower magnifications using a stereomicroscope and a digital camera. In the case study detailed below, the photographic series has been incorporated into the project archive.

Sample Archiving

Another useful practice is sample splitting and archiving whenever possible. As noted above, material archived at the Rafter Radiocarbon Laboratory, GNS Science, New Zealand, allowed Allen and Wallace (2007) to identify the presence of *Cordia subcordata* in a previously analyzed ^{14}C sample from Bellwood's (1978) excavations. In this case, bulk charcoal dates (Bellwood 1978; Allen 1994) were compared with new AMS results from the same proveniences and anomalies identified. Subsequent examination of archived materials from the Rafter laboratory identified *Cordia* as a major sample component. These findings aided both local vegetation reconstructions and, more importantly, helped resolve age differences between prior ^{14}C analyses and new AMS results on short-lived materials from the same proveniences. Wallace and Green (2012) undertook a similar analysis at the historically significant Maioro site (New Zealand). Again using samples archived at Rafter Radiocarbon Laboratory, they identified at least two long-lived species, one that was problematic with respect to their ^{14}C results and another that was not. The latter, *Vitex lucens*, has a propensity to regrow from fallen trunks and residual roots, and apparently continued to be available for fuel and other uses following forest clearance but probably in an immature form.

POLYNESIAN CASE STUDY

Background

Moturakau Rockshelter (MR-1), a stratified site first ^{14}C dated in the 1980s and more recently resampled for chronological analyses (using extant collections), illustrates some of the foregoing issues and recommended solutions. The site is situated on Moturakau Islet, which lies within the 54-km^2 lagoon of the "almost-atoll" of Aitutaki, southern Cook Islands (18°51′45″S, 159°48′10″W) (Figure 2) (Stoddart and Gibbs 1975). The rockshelter is comprised of two small clefts eroded into a bedded palagonitic lapilli tuff (Wood and Hay 1970) on the leeward side of the islet, referred to here as Shelter A and Shelter B. A 16-m^2 excavation identified a well-stratified deposit, which was originally dated using 12 bulk samples of unidentified wood charcoal (Allen 1992, 1994). More recently, AMS dating on short- and medium-lived materials was carried out to evaluate prior determinations, particularly those from the lower half of the deposit. The suite of ^{14}C determinations has been integrated into a Bayesian-supported geochronological model of site formation (Allen and Morrison 2013). Analyses of the rockshelter features, fauna, artifact assemblages, and ^{14}C results indicate that this was an important campsite, probably from the 12th century AD onwards, associated with fishing and adze production (details in Steadman 1991; Allen 1992, 2002; Nicholls et al. 2003; Allen and Craig 2009; Ditchfield 2010).

Methods

The recent chronometric study specifically targeted previously sampled proveniences to facilitate comparisons of prior and new results. An effort was made to select (1) short-lived materials (10 yr or less) or juvenile specimens; (2) marine materials that were arguably local in origin, to en-

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sure use of an appropriate ΔR value; and (3) specimens that had unambiguous associations with cultural activities. With respect to the latter, Higham and Petchey (2000:263) observe that precise archaeological dating begins with "the careful mapping of the stratigraphic location of the cultural remains, the documentation of the contextual association between the material selected for dating, and the inferred cultural activity or archaeological event which is to be dated." As archaeologists are acutely aware, high-caliber chronology building requires tight control over sample provenience and exclusion of contexts that may have experienced postdepositional disturbances. However, the vulnerability of often small, singular AMS samples to taphonomic processes is not as widely appreciated. Higham and Petchey's criteria for assessing the strength of sample-event associations (Table 3) is a useful reminder of ideal contexts for dating and, when these are not available, an explicit basis for systematically considering sample-event relations in less desirable contexts. In the present case, sampling targeted intact features and discrete charcoal concentrations as recognized in excavation, or exposed and cleaned profiles when available (similar approaches are described in Rolett 1998; Kirch et al. 2004, 2010; Kahn 2006 and others).

The archaeological specimens were identified by JMH (flora) and MSA (fauna) using reference collections of wood and other plant parts (including charred examples), skeletonized vertebrates, and marine mollusks held at the University of Auckland, Department of Anthropology. These collections are fairly comprehensive in terms of the more common East Polynesian plants and animals that were likely to have been used by human populations. Multiple individuals from different archipelagos are available in several cases. The archaeobotanical reference collection includes 350 Pacific specimens and, in the main, the wood samples are supported by herbarium vouchers that have been verified by botanists. The vertebrate reference collection includes 1100 specimens from New Zealand and the tropical Pacific, and the shell collection is comprised of 377 tropical Pacific taxa.

Previously analyzed samples were processed at Beta Analytic, Inc., Miami (indicated by the prefix Beta-) following procedures outlined on their web site (http://www.radiocarbon.com/), while the new AMS determinations were made at both Beta Analytic and ANSTO (Australian Nuclear Science and Technology Organisation; indicated by prefix OZ-) following procedures described in Fink et al. (2004). The conventional ^{14}C ages were calibrated using OxCal v 4.1.7 (Bronk Ramsey 2009). For marine samples, the Marine09 ^{14}C age curve (Reimer et al. 2009) was used, along with a ΔR value of 18 ± 21 yr derived from known-age shells (Petchey et al. 2009:2242). For terrestrial samples, the SHCal04 atmospheric curve (McCormac et al. 2004) was used following Petchey et al.'s (2009) advice for the southern Cook Islands.

The taxa and materials analyzed in the recent AMS analyses included two plant materials with short lifespans (*Pandanus* sp. and *Cocos nucifera*). Other short- to medium-lived materials included marine eel (Muraenidae) and fish bone (Holocentridae), pearl-shell (*Pinctada* cf. *margaritifera*), and fragments of one of the smaller giant clams, probably *Tridacna maxima* but *T. squamosa* is also a possibility. The suitability of each material and the potential for inbuilt age are briefly considered below and examples of photographic documentation are provided in Figures 3 and 4.

OZN805, OZN809, and OZO699 consisted of *Pandanus* sp. drupe (fruit) fragments (Figure 3A, 3B). *Pandanus* trees are common in Pacific coastal settings and considered native to East Polynesia, although they also may have been introduced by Polynesian settlers. The kernels of the syncarpus fruit, found within the drupes or phalanges, were a snack or famine food, both in the Cook Islands (Buck 1934: 136) and elsewhere in the Pacific, particularly on atolls (Denham 2007; Whistler 2009). *Pandanus* grows on Moturakau Islet today, and it is likely that the recovered specimens were food remains, although they may have simply been used as fuel (see Di Piazza 1998, 1999).

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Table 3 Criteria for evaluating the strength of association between cultural event and ^{14}C sample (adapted from Higham and Petchey 2000, based on Mook and Waterbolk 1985).

Strength of determination	Criteria[1]	Example[2]
Robust	Target event and determined age have no offset or bias because the material *is* that event.	Bones where the age of the animal's death is sought; modified shells where shell collection and meat extraction is the target event; charred short-lived materials from *in situ* vegetation clearance where the date of the fire is sought.
Very strong	There is a strong possibility that the material dated and the event share the same true age, as implied by functionality and context.	Samples of identified short- or medium-lived materials from a hearth or oven.
Strong	An absolute direct relationship between the event and the dated material is lacking, but there is a realistic expectation that they are contemporaneous.	Samples of identified short- or medium-lived materials from well-defined lens within occupation layers; shells from a feature within an occupation layer where other food-processing activities are indicated.
Tentative	Dated material is only related to the event on the basis of an interpretation, which may or may not be robust. Additional information may be necessary to evaluate associations with the event of interest.	Dispersed charcoal from agricultural soils that may date the agricultural activity but also could date pre-agricultural forest; charcoal from a post-mold, which could date the post but also could be secondary fill.

[1]Note that this set of criteria relates mainly to association.
[2]The examples provided in Higham and Petchey have been modified.

OZN808 and OZN806 were coconut shell fragments (Figure 3D). Coconut fruits mature within roughly a year (Jayasuriya and Perera 1985) and, as with *Pandanus* drupes, coconut shell is sometimes used as a fuel (e.g. Di Piazza 1998).

OZN807 was a Holocentridae (squirrelfish) premaxilla (Figure 3A). This taxon previously provided results that were consistent with other marine materials (pearl-shell) from the same provenience in another Aitutaki dating study (Petchey et al. 2009). Holocentridae is a tropical fish family of relatively small inshore species that frequent coral reef and rocky bottom habitats. Although the lifespans of Holocentridae species are poorly known, captivity records, body size, and characteristics of coral reef fish in general suggest that members of this family probably live for less than a decade (Steele et al. 2009:225). A Muraenidae or Moray eel vertebra, most likely from a marine species given the local environment, also was analyzed (Beta-307830, Figure 4C). Although anecdotal accounts suggest that morays can live for up to 30 yr or more, the small size of the vertebra used in the present analysis suggests a young adult. Pretreatment and quality assurance procedures for these two samples are described in Allen and Morrison (2013:4567).

Pearl-shell (*Pinctada margaritifera*), a filter-feeding species, is recommended by Petchey (2009) as a reliable material for dating, although she cautions that the rate of exchange between lagoons and open-ocean waters can affect specimens. Published accounts suggest pearl-shell lifespans of 10 to 15 yr are common in commercial environments (Chávez-Villalba et al. 2011; Intes 1984). Anecdotal evidence indicates that pearl oysters may live for up to 30 yr, but this is unsubstantiated. Pearl-shell has the added advantage of being an important raw material for tools and ornaments and culturally modified specimens can be directly linked to cultural activities (Figure 4B). Use of pearl-shell in ^{14}C

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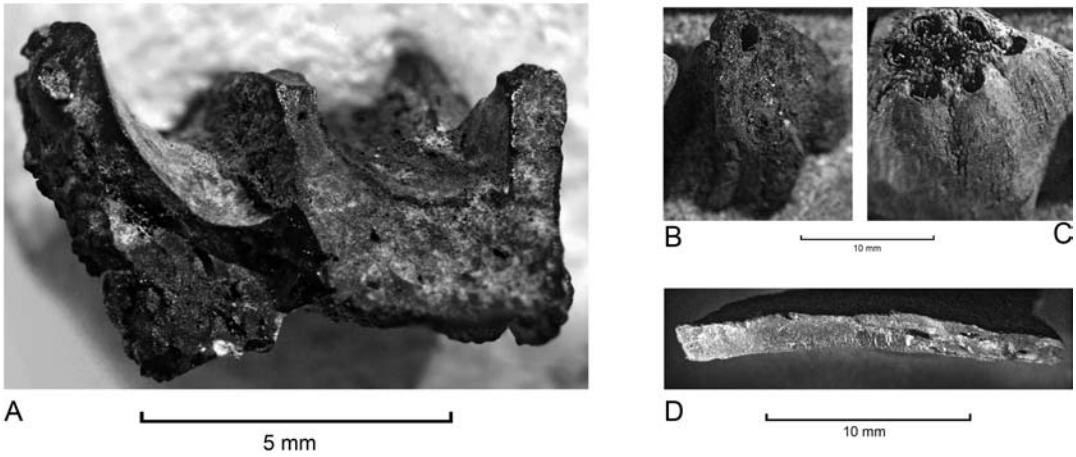


Figure 3 Plant samples (lab numbers): A: *Pandanus* sp. drupe (OZN805); B: *Pandanus* sp. drupe (OZO699); C: *Pandanus* sp. drupe, modern reference sample; D: *Cocos nucifera* endocarp (OZN808). Photos by T Mackrell (A) and JMH (B–D).

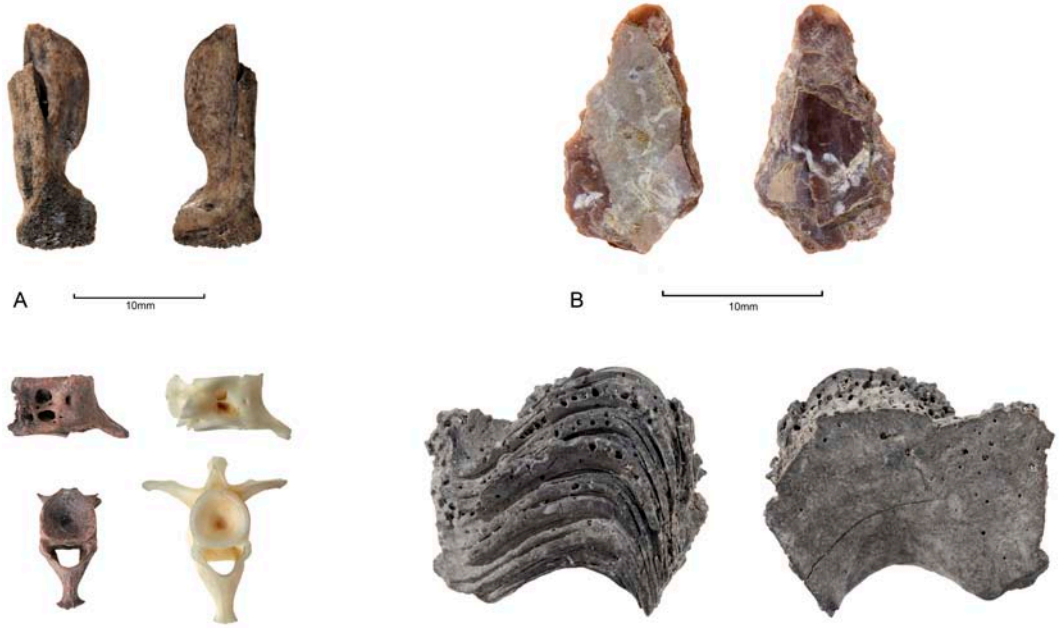


Figure 4 Faunal samples (lab numbers): A: Holocentridae (fish) premaxilla (OZN807); B: culturally modified *Pinctada* cf. *margaritifera* (pearl-shell) (OZN804); C: Muraenidae (eel) vertebra bone, modern reference sample on right, archaeological sample on left (Beta-307830); D: *Tridacna* cf. *maxima* (clam) shell fragment (Beta-307829). Photos by T Mackrell.

dating also requires consideration of where the shell originated. The most parsimonious argument in the present case is that the specimen derived from the local lagoon, as Gibbs (1975) recorded *Pinctada* in his marine survey.

Finally, a burnt valve fragment of *Tridacna* cf. *maxima*, one of the smaller giant clams, was analyzed (Beta-307829) (Figure 4D). Shells of this taxon are considered a relatively reliable dating material but with some provisos (see Petchey and Clark 2011). All tridacnid species have the potential to be moderately long-lived and *T. maxima* in particular are estimated to live for in excess of 50 yr (e.g. McMichael 1974; McKoy 1979). Additionally, the exceptionally dense character of tridacnid

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shells makes them highly resistant to weathering and thus susceptible to extended surface residence. The size and thickness of the Moturakau sample suggested a small value and by extension a relatively young individual, probably less than 20 yr in age; we consider this particular specimen to be medium-lived. A residual of this specimen was archived.

Results

Overall, the new ^{14}C results are in good agreement with earlier analyses (Figure 5). Three determinations (shaded in gray) are outliers, as identified both manually and statistically (specifics in Allen and Morrison 2013; see also Bronk Ramsey 2009). Postdepositional disturbances seem to be responsible in one case (Beta-OZN806), a coconut shell sample derived from screening of the general sediment matrix. A mixed diet apparently contributed to the anomalous marine eel (Beta-307830) result, but even after application of a mixed marine-terrestrial calibration curve, the result remains an outlier (details in Allen and Morrison 2013).

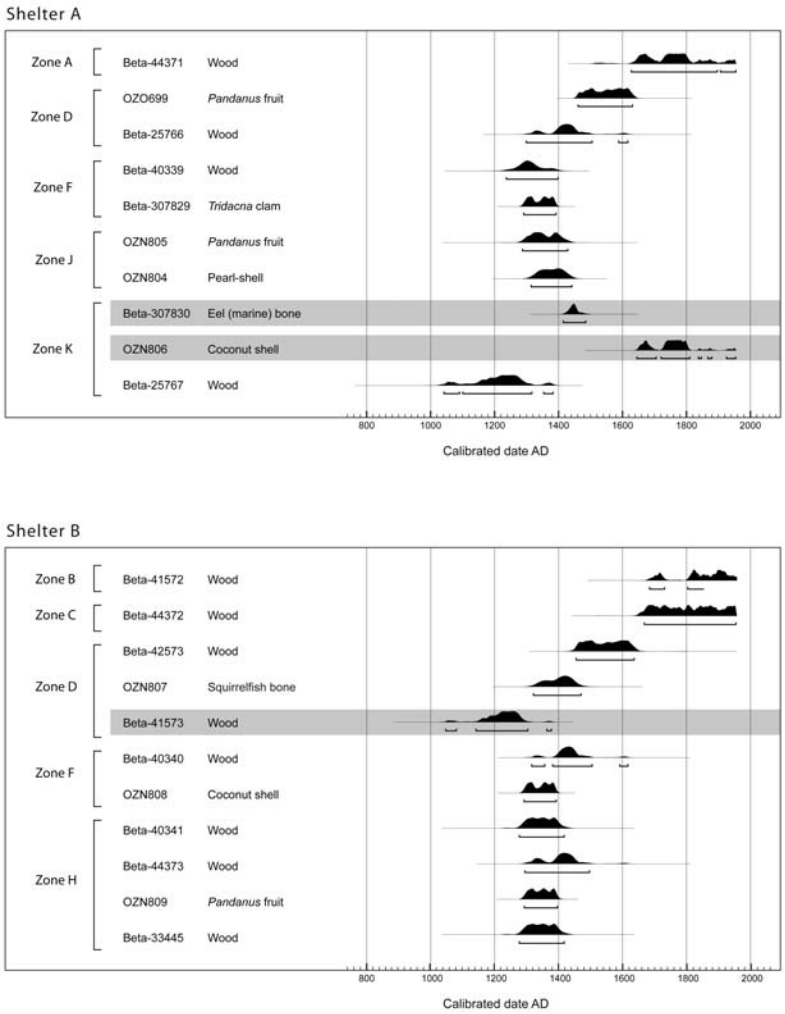


Figure 5 ^{14}C determinations from the two adjacent shelters of Moturakau Rockshelter with outliers shaded in gray (sample and calibration details in text and Allen and Morrison 2013).

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Of the 11 prior analyses on bulk wood charcoal (Allen 1994) only one sample, Beta-41573, is likely to be affected by inbuilt age. If the materials had been photographed in the 1990s, then an identification might now be possible, but this was not the case. Similarly, there is no archived residual, as the entire sample was used in the original ^{14}C analysis. While direct information on the taxonomic composition of the sample has been lost, circumstantial evidence allows us to build a case for a likely contributor. Moturakau Islet is today thickly covered in woody vegetation despite its small size. The local name translates as "islet of wood," suggesting this tiny volcanic remnant has been forested for some time. During the 1989 field study, *Calophyllum inophyllum* trees dominated the leeward coastal flat (Figure 6), as was also the case during Raymond Fosberg's (1975:79) botanical survey a decade earlier. In examining curated wood charcoal samples from Moturakau Rockshelter, JMH found that five out of eight contained *C. inophyllum* wood. Several of these were from the basal occupation (Zone K), and in some cases this taxon was an assemblage dominant (Table 4). In general, *C. inophyllum* can reach large proportions and some of the Moturakau individuals observed in 1989 were close to 100 cm in girth and 20 m or more in height. While the maximal lifespan of *C. inophyllum* is not known, in a Malaysian case this species attained a diameter at breast height of 50 cm within a 70-yr period (Soerlanegara and Lemmens 1994) and anecdotal records suggest the species can live for up to a century. It is likely that Beta-41573 of Zone D included mature *Calophyllum* wood, given the prevalence of this taxon in other shelter samples and the persistence of very large, presumably aged, individuals on the island today.



Figure 6 *Calophyllum inophyllum* forest of Moturakau Islet, Aitutaki. *Calophyllum* trees surround (upper image) and tower over (lower image) the thatched house of the 1989 field camp. Several large trees were blown over in a recent cyclone, possibly Tropical Cyclone Pat (category 3/5) in 2010. Photos by MSA.

With respect to the biogeography of the species, Guppy (1906) notes that *Calophyllum* seeds can float but also may be distributed by birds as they are sticky, suggesting at least two natural dispersal mechanisms. Fosberg (1975:79) concurred, classifying *C. inophyllum* as indigenous, while noting that the Cook Islands are the eastern limit of its natural floristic distribution. He also allowed, how-

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ever, that it could have been a Polynesian introduction. On Aitutaki, *Calophyllum* mainly occurs on the mainland and the two volcanic islets of Moturakau and nearby Rapota. Its absence on Aitutaki's coralline islets probably reflects edaphic limitations. The archaeological results demonstrate regular use of *Calophyllum* wood for fuel throughout the 700-yr occupation. They also establish the presence of *Calophyllum* in the earliest occupation zone of Moturakau Rockshelter, which is (on present evidence) within the earliest period of early human activity on Aitutaki, and in the southern Cook Islands generally (Allen and Morrison 2013; Kirch et al. 1995). Although not definitive, in our view the archaeological evidence, which points to an abundance of mature trees at an early point in time on a islet where occupation was short term, is most supportive of the hypothesis that *Calophyllum* is an indigenous, naturally dispersed species, as originally argued by Fosberg (1975).

Table 4 Distribution of *Calophyllum inophyllum*, as observed in bulk wood charcoal samples from Moturakau Rockshelter that were examined for the recent AMS dating project.[1]

	Shelter A						Shelter B	
	11	62	64	248	249	246	198	199
	TP1	TP1	TP1	TP13	TP14	TP16	TP7	TP7
Taxon	Zone D	Zone J	Zone K	Zone K	Zone K	Zone K	Zone F	Zone H
Calophyllum inophyllum			+++	++	++	++		+++
Cordia subcordata					+			
Thespesia populnea			+					
Guettarda speciosa			+					
Sapotaceae			+					
Unidentified A-246						+		
Cocos nucifera endocarp	+		+				++	+
Pandanus drupe	+	+						+++
Undetermined wood		++	++		+		++	+
Monocot tissue							+	+

[1]Crosses indicate relative abundance in sample; all materials are wood charcoal unless otherwise indicated.

DISCUSSION AND CONCLUSIONS

The Moturakau case study illustrates how the recommendations offered at the outset might assist in improving Polynesia's archive of ^{14}C results. The recent Moturakau chronometric study might have begun by first reviewing archived residuals from Allen's (1992, 1994) prior analysis and then assessing photographic documentation of particular ^{14}C submissions. However, many samples were submitted in their entirety to meet the requirements of standard ^{14}C dating at the time and no documentary photographs were taken. While wood identification work was carried out, it was for the purposes of vegetation reconstruction (Murakami in Allen 1992). The recent chronometric study has made progress on both fronts (e.g. Figures 3 and 4).

One finding of the recent study was that short-lived materials often were not available, despite the recovery of large amounts of charcoal from the 16-m^2 excavation area at Moturakau Rockshelter, and access to two experienced wood charcoal analysts (JMH and Dr Rod Wallace). Thus, the ideal selection criteria for dating (short-lived taxa from discrete cultural features, as per Table 3) could not always be implemented. In attempting to identify short-lived materials for AMS dating, it soon became apparent that *Calophyllum inophyllum* was an important fuel source throughout the Moturakau sequence. The outlier Beta-41573 further suggests a long-lived species on the islet, probably *Calophyllum* given its prevalence in other samples and its dominance in the extant islet forest.

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Another finding was that the new results on identified materials were in large part supportive of prior age assignments made on unidentified bulk wood charcoal. Burley (2013) recently reported a similar outcome from his redating of early Tongan sites. While we suggest that dating of short-lived taxa is preferable, both his analysis and ours indicate that unidentified bulk charcoal samples *may* provide accurate results and these kinds of samples need to be assessed rather than dismissed outright (see also Wallace and Green 2012). By targeting previously sampled proveniences, comparisons between results on short-lived materials and prior determinations on unidentified or otherwise less-secure materials were facilitated. This not only allowed prior age estimates to be verified, but increased the pool of results from any given provenience and by extension enhanced statistical assessments and chronological modeling (i.e. Allen and Morrison 2013).

The Moturakau case also illustrates the value of high-resolution photography as an archival tool, useful to both future studies at this site and for comparisons with other localities. Had Allen (1992, 1994) photographed the original ^{14}C specimens, identifications might now be possible. Identifications not only would have aided assessments of inbuilt age, but also contributed to our understanding of past vegetation and traditional fuel practices. Notably, some samples *were* identified to species and photodocumented at the time (Murakami in Allen 1992), but for paleoecological reconstructions not ^{14}C dating; Spriggs and Anderson's (1993) critique had not yet been written and the potential for inbuilt age in tropical trees was not fully appreciated by the Pacific archaeological community.

Over the last two decades, as our understanding of the ^{14}C method has evolved, numerous well-known sites have been revisited for further sampling, clarification of outstanding chronological questions, and application of new dating approaches (e.g. Rolett and Conte 1995; Hunt and Lipo 2006; Anderson and Sinoto 2002; Allen and Wallace 2007; Dye and Panteleo 2010; Molle and Conte 2011; Allen and McAlister 2013; Burley 2013). It is easy to imagine how this process of reassessment might have been facilitated, and time and money saved, had the original ^{14}C samples been more fully documented both descriptively and photographically. Fuller documentation prior to destructive analysis also might aid in determining where and how new samples should be taken as ^{14}C technologies and understanding of the factors that affect results improve. In this respect, we also suggest there is a value to archiving portions of critical samples for future study whenever possible. Not only are excavations and ^{14}C dating destructive, but archaeological resources are under increasing threat from both modern developments and natural processes such as erosion and sea-level rise (e.g. Erlandson 2008).

Lastly, information on the breadth and origin of reference collections used in taxonomic determinations of ^{14}C samples, and the analysts involved in the identification process, would be helpful to future research efforts. Our ability to identify both short- and long-lived material is a direct outcome of the quality of our reference collections, combined with continually improving equipment (e.g. desktop scanning electron microscopes) and new technologies (e.g. 3D scanners). Knowledge of the composition and character of the reference collections used at the time can be helpful in understanding why certain determinations were made, the tools used, as well as their accuracy and/or consistency with current taxonomy.

The recommendations outlined here are aimed at improving the quality of ^{14}C results and the construction of reliable chronologies over the short term, while facilitating reappraisals in the future, long after samples have been offered up for the essential, but nonetheless destructive, process of ^{14}C dating.

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