High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia

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The 15 archipelagos of East Polynesia, including New Zealand, Hawaii, and Rapa Nui, were the last habitable places on earth colonized by prehistoric humans. The timing and pattern of this colonization event has been poorly resolved, with chronologies varying by >1000 y, precluding understanding of cultural change and ecological impacts on these pristine ecosystems. In a meta-analysis of 1,434 radiocarbon dates from the region, reliable short-lived samples reveal that the colonization of East Polynesia occurred in two distinct phases: earliest in the Society Islands A.D. ∼1025–1120, four centuries later than previously assumed; then after 70–265 y, dispersal continued in one major pulse to all remaining islands A.D. ∼1190–1290. We show that previously supported longer chronologies have relied upon radiocarbon-dated materials with large sources of error, making them unsuitable for precise dating of recent events. Our empirically based and dramatically shortened chronology for the colonization of East Polynesia resolves longstanding paradoxes and offers a robust explanation for the remarkable uniformity of East Polynesian culture, human biology, and language. Models of human colonization, ecological change and historical linguistics for the region now require substantial revision.

During the last prehistoric expansion of modern humans, Polynesians from the Samoa-Tonga area dispersed through more than 500 remote, subtropical to subantarctic islands of East Polynesia (a cultural region encompassing the islands of New Zealand, Chathams, Auckland, Norfolk, Kermadecs, Societies, Cooks, Australs, Gambier, Tuamotu, Marquesas, Line, Rapa Nui, and Hawaii), an oceanic region the size of North America (Fig. 1). The timing and sequence of this expansion, debated vigorously since Europeans rediscovered the islands of East Polynesia (1, 2) and most intensively with the advent of radiocarbon dating (3, 4), remains unresolved. On many islands, irreconcilable long and short settlement chronologies coexist that vary by more than 400–1,000 y (4). These conflicting chronologies preclude establishment of a regional pattern of settlement and hinder our understanding of cultural change and ecological impacts on these island ecosystems.

The last systematic analysis of radiocarbon dates from archaeological and paleoecological sites throughout East Polynesia, published 17 y ago, was based on 147 radiocarbon dates (5). It used a "chronometric hygiene" protocol to exclude dates with high uncertainty and to provide a chronology that proposed initial settlement A.D. 300–600 in the Marquesas, A.D. 600–950 in the central, northern, and eastern archipelagos, and no earlier than A.D. 1000 in New Zealand. This analysis shortened East Polynesian prehistory just at the time when accelerator mass spectrometry (AMS) radiocarbon dating became available for very small samples (e.g., individual seeds). Subsequent studies using precise AMS dating of short-lived materials alone have generally supported short chronologies (4, 6–8). However, these chronologies continue to be dismissed by some scholars (9, 10) on hypothetical grounds of missing evidence or archaeological invisibility, and in favor of radiocarbon dates on materials (typically unidentified charcoal with high inbuilt age potential) incapable of providing a precise age for the event being dated. Conflicting estimates for initial colonization in East Polynesia create great uncertainty about the historical framework within which human mobility and colonization, variations in human biology and demography, and the rates and types of human-induced ecological impacts to island ecosystems must be explained.

As the number of radiocarbon dates from East Polynesia has increased 10-fold over those available in 1993 (5), an attempt to resolve the frustrating problem of colonization chronology for the region is now opportune. Our main objective is to establish the most accurate age, or ages, for initial colonization in East Polynesia. To accomplish this, it is necessary to be conservative in evaluating the usefulness of data. That is, to accept only those dates that (*i*) are clearly and directly linked to cultural activity, (*ii*) have the fewest intrinsic sources of potential error (e.g., from inbuilt age, dietary, or postdepositional contamination by old carbon), and (*iii*) are capable of providing a calibration that is close to the "true" age of the actual target event (i.e., human activity). One approach is to evaluate dates within their individual and comparative stratigraphic levels according to criteria of "chronometric hygiene" (11, 12) and build from those results toward a regional overview; but this method can be subjective, and it is impractical when dealing with very large databases, as is the case here. Instead we have chosen a "top-down" approach to evaluate the entire archaeological radiocarbon database for East Polynesia as a single entity. This allows radiocarbon dates, irrespective of stratigraphic context, to be categorized according to accuracy and precision, and for patterns of age and distribution of colonization to be sought accordingly upon the most reliable dated materials. Here accuracy is defined based on those samples that can provide a date that is the "true" age of the sample within the statistical limits of the date. Precision is controlled by small laboratory measurement and calibration errors.

Here, we assemble 1,434 radiocarbon dates from at least 45 East Polynesian islands covering all of the major archipelagos (Fig. 1), that are in direct association with cultural materials or commensals (e.g., *Rattus exulans*). We included dates ranging from 300 to 3,000 ^{14}C years before present (y BP) to exclude modern dates, and to include the earliest possible age for expansion from West Polynesia (Table S1). We first categorized all radiocarbon-dated materials into one of six sample material types: short-lived plant, long-lived plant, unidentified charcoal, terrestrial bird eggshell, bone, and marine shell (Fig. 2). Dates on these materials were then sorted into reliability classes, according

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See Commentary on page 1753.

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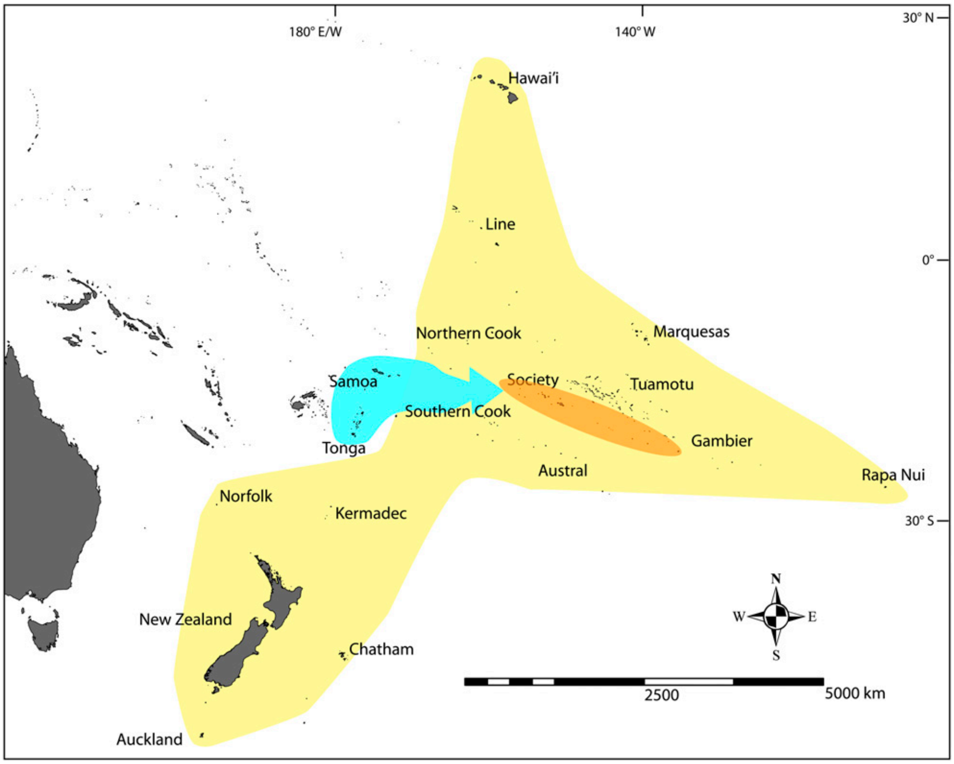

Fig. 1. Islands of East Polynesia, summarizing the two phases of migration out of West Polynesia (blue shading): first to the Society Islands (and possibly as far as Gambier) between A.D. ∼1025 and 1121 (orange shading), and second to the remote islands between A.D. ∼1200 and 1290 (yellow shading).

to whether there was potential for any disparity between the age of the radiocarbon event (i.e., ^{14}C fixation) and the time of the target event (human activity) through processes such as inbuilt age or imprecise calibrations (*Materials and Methods,* Fig. 3, and Table S1). Calibration probabilities were then calculated for the subset of reliable dates to derive the most precise (within radiocarbon calibration error) estimate for the age of initial colonization on all East Polynesian island groups (*Materials and Methods* and Fig. 4).

Results and Discussion

The proportion of radiocarbon-dated sample materials in each overall reliability class is shown in Fig. 2. Class 1 dates are dominated by short-lived plant materials (such as small twigs, leaves, and seeds) in contrast to Class 2 and 3 dates, which are dominated by long-lived plant remains and unidentified charcoal, sample types that are often unreliable, as they can introduce substantial error through in-built age. The high proportion of unidentified charcoal in Class 3 shows this category of dated materials in the dataset also tends to have large measurement errors.

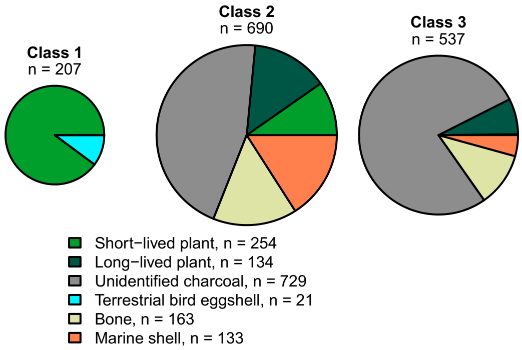

Fig. 2. Proportion of radiocarbon-dated sample materials making up each overall reliability class (data from Table S1). Diameter proportional to square root of *n*.

The distribution of calibrated age ranges for all classes of radiocarbon dates shows a clear pattern across the entire region (Fig. 3); without exception, the range for all Class 1 calibrated dates (68% probability; $n = 207$) is considerably narrower than it is for Class 2 and 3 dates, regardless of their individual stratigraphy or context. Class 1 calibrations range only from A.D. 1025 to 1520, in contrast to those of Class 2–3 dates, which extend back to 500 B.C. This pattern reflects the higher precision and accuracy of the reliable targets that make up Class 1 dates (i.e., short-lived materials with SEs <10%), whereas the extended ranges of Class 2 and 3 dates correspond with greater imprecision from inbuilt age and marine calibration problems associated with the unidentified charcoal and marine shell dates that dominate these classes (Fig. 2). Radiocarbon dates in Classes 2 and 3, despite providing imprecise calibrations, have formed the basis of arguments for settlement across East Polynesia in the first millennium A.D. or earlier (13).

Calibrated age ranges for each Class 1 radiocarbon date, and their cumulative and summed probabilities, are shown for each archipelago or island where they occur, with our Early Age Estimation Model (EAEM) providing the earliest likely date, and the Late Age Estimation Model (LAEM) the latest likely date (*Materials and Methods* and Fig. 4) for colonization. Using our models, we can show a robust and securely dated two-phase sequence of colonization for East Polynesia: earliest in the Society Islands A.D. ∼1025–1120, four centuries later than previously assumed, and significantly before (by ∼70–265 y) all but one (Gambier) of the remote island groups with Class 1 dates. These remote islands, from the tropic to sub-Antarctic oceans, were all colonized in one major pulse between A.D. 1190 and 1293 (Fig. 4 *A* and *B*). Age estimates for initial colonization of the Gambier archipelago are unusually broad (167-y difference between the EAEM and LAEM, i.e., between A.D. ∼1108 and 1275) compared with all other islands (average difference of 55 y between earliest and latest estimates). This is caused by one date in the Gambier group [Beta-271082: 970 ± 40 BP on carbonized *Hibiscus* wood (14)] that is significantly older than the rest

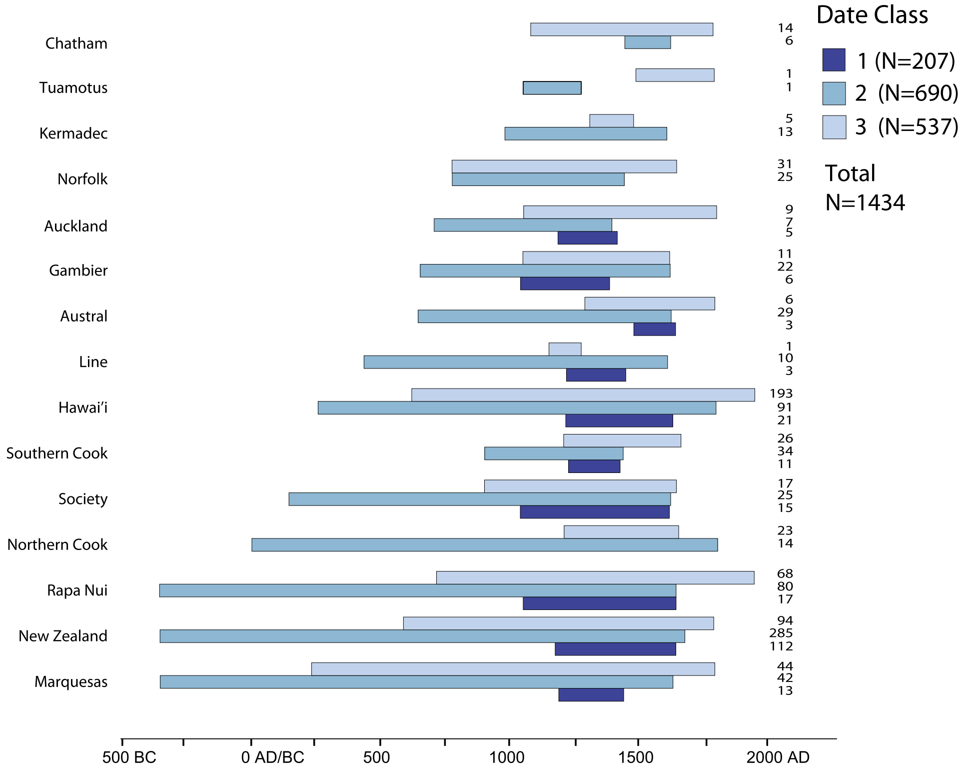

Fig. 3. Chronometric range (68% probability) of calibrated radiocarbon dates for East Polynesian islands, for reliability Classes 1–3 as defined in *Materials and Methods*. Boxes show minimum and maximum calibrated ages for dates within each class. The reliable Class 1 dates consistently reveal a short chronology for each island or archipelago where data are available. In contrast, Class 2–3 dates, which are based on materials that have a high risk of imprecision and/or inaccuracy, have a larger spread of ages, and these are often used to support longer chronologies in the region.

(Fig. 4*A*), leaving initial colonization age ambiguously between that of the central and marginal East Polynesian islands. It is conceivable that the Gambiers were found during early island hopping eastward from the Society Islands, but more dating of short-lived materials is needed to support that proposition.

New Zealand's well-established short colonization chronology (11), which was further shortened and refined by dates from nonarchaeological sites on short-lived woody seed cases gnawed by the Polynesian-introduced *Rattus exulans* and compared with terrestrial avian eggshell from an early human cemetery (4, 15), and the short colonization chronology for Rapa Nui (6), are both confirmed here (EAEM–LAEM range: A.D. ∼1230–1282 and A.D. ∼1200–1253, respectively) but with much larger sets of Class 1 dates. This clearly demonstrates that even a relatively small subset of precise radiocarbon dates on highly reliable samples is capable of providing a secure chronology, both from relatively small islands such as Rapa Nui, and from New Zealand, the largest and most topographically complex island group in Polynesia. More striking are the results from the Marquesas and Hawaiian archipelagos which now indicate a much shorter chronology (EAEM–LAEM range: A.D. 1200–1277. and A.D. ∼1219–1266, respectively), some 200–500 y later than widely accepted (16, 17), placing them in close agreement with both New Zealand and Rapa Nui. They are also in close agreement with age estimates for initial colonization on the remaining island groups, with Class 1 dates including Line, Southern Cooks, and the sub-Antarctic Auckland Island, which all show remarkably contemporaneous chronologies within radiocarbon dating error (Fig. 4*A*). The unity in timing of human expansion to the most remote islands of East Polynesia (encompassing the triangle made between Hawaii, Rapa Nui, and Auckland Island) is even more extraordinary considering these islands span a vast distance of both longitude and latitude (Fig. 1). Collectively, these results, based on only the most reliable samples, provide a substantially revised pattern of colonization chronology for East Polynesia, which shortens the age for initial colonization in the region by up to 2,000 y, depending on various claims asserted for earlier chronologies (3, 9, 10). The results also shorten by centuries the chronologies proposed for East Polynesian islands by Spriggs and Anderson (5), and confirm the growing trend of shorter chronologies emerging from recent studies on individual East Polynesian islands (3, 4, 6, 7, 18).

The consistent age ranges on short-lived samples for colonization on islands in the far reaches of East Polynesia imply reliable measurement of the same dispersal and colonization event over this vast region. This is an important result that has implications for colonizing process (discussed below). More radiocarbon dating of short-lived materials from islands lacking enough Class 1 dates for robust chronologies (Gambier, Tuamotus, Australs, Northern Cooks, Kermadec, Norfolk, and Chathams; Fig. 3) is desirable to further test the pattern. In addition, closer scrutiny of dates at the older end of the Class 1 age ranges may also increase the precision of estimates for initial colonization. For example, some of the oldest dates for the Auckland Islands are based on small-diameter (2-cm) wood from long-lived trees (*Dracophyllum* spp. and *Metrosideros umbellata*), which, despite the size of twigs, may still contain inbuilt age and create an artificial tail to the probability distributions (19).

The narrow age distribution of colonization through remote East Polynesia is not explained as merely a function of analyzing smaller subsets formed by Class 1 dates. Rather, our results indicate, quite simply, that widely accepted, longer chronologies for the region have been founded on materials (i.e., unidentified charcoal, long-lived plant materials, bone, and marine shell) that are inappropriate for precise radiocarbon dating of a relatively recent event, and where large measurement errors, ΔR variability, calibration issues, and additional uncertainties (e.g., from inbuilt age or contamination) associated with such samples can lead to inaccuracy and imprecision. It is no longer reasonable to argue that evidence of earlier settlements is "missing" or archaeologically invisible through sampling or taphonomic problems [Discussion in (4)], or that particular radiocarbon dates upon specifically unidentified samples, or samples with weak stratigraphic connections to cultural remains make a case for

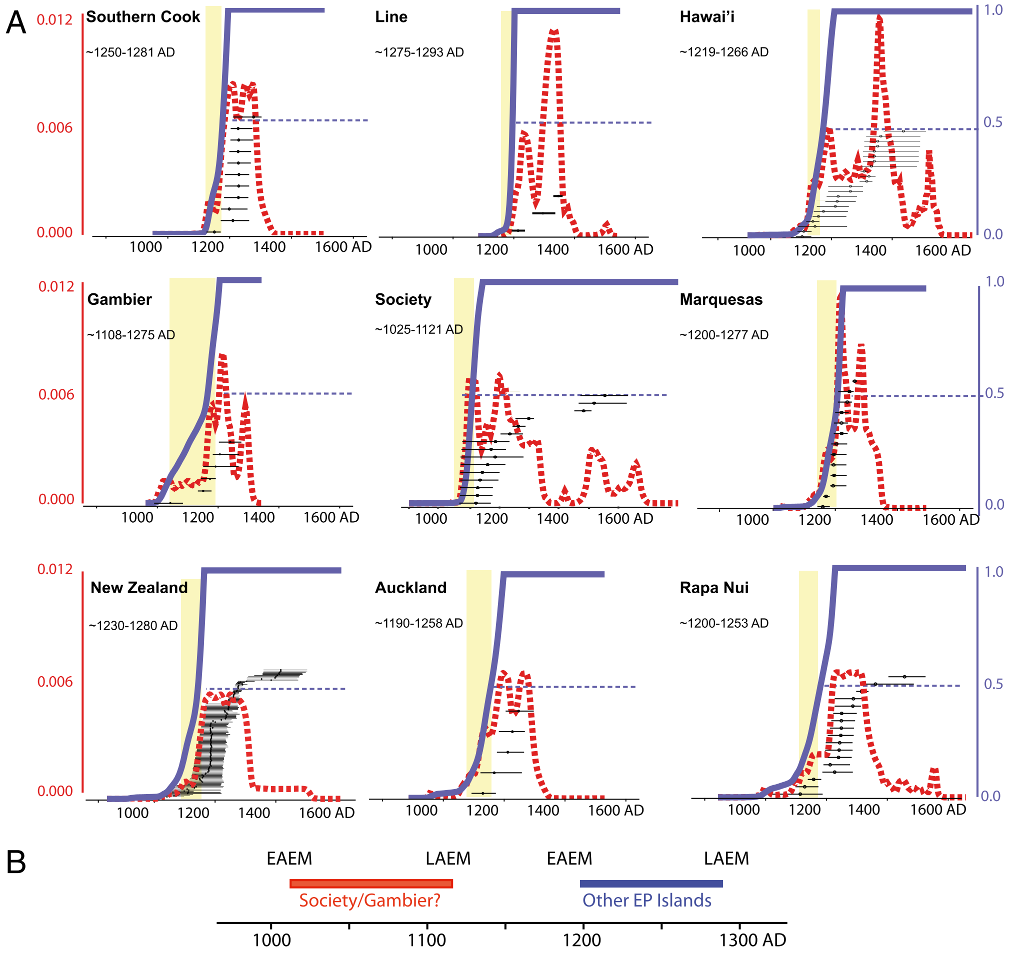

Fig. 4. (*A*) Estimates for the timing of colonization for East Polynesian archipelagos or islands. For each graph, individual ranges (68% probability) of Class 1 calibrated radiocarbon dates are shown as black horizontal lines; circles represent median (bottom axis). Red dashed line indicates sum of probability distributions (left axis). Solid blue line = cumulative probability (right axis) which provides a means of assessing our confidence that colonization occurred no later than a particular date. For the Society Island dates, this was set to A.D. 1200 based on the assumption that we have 100% confidence that colonization had occurred by this time; and for the remaining islands with Class 1 dates, this was set to A.D. 1300. Blue dashed line represents LAEM in years A.D. Our LAEM and our EAEM for initial colonization are listed below each island group and are represented by the yellow band. (*B*) Distinct separation between colonization ages for the Society Islands (and possibly Gambier) vs. other eastern Polynesian islands.

earlier ages of colonization (9, 10). The consistent, contemporaneous nature of East Polynesian age distributions is better explained by extraordinarily rapid migration from the centrally positioned East Polynesian islands in the 13th Century.

Migration into eastern Polynesia began after a 1,800-y pause since the first settlement of Samoa, ~800 B.C. (12), which implies a relatively sudden onset of whichever environmental or cultural factors were involved. Our results show that, quite soon after reaching the central islands, Polynesian seafarers discovered nearly every other island of the eastern Pacific within about one century, a rate of dispersal unprecedented in oceanic prehistory. This might be explained, in cultural terms, by rapid population growth on relatively small islands, purposeful exploration, and technical innovation in sailing vessels, such as the advent of the double canoe that effectively erased distance as a barrier to long-range voyaging (c.f. European voyaging in the Atlantic and Indian Ocean in the 15th century). However, environmental factors or disaster could also have been influential. Our data have narrowed the coincidence of dispersal throughout East Polynesia (A.D. ~1200–1300) to a period of peak El Niño occurrence during the last millennium, when increased frequencies of tropical westerly and subtropical easterly winds favored access to the more remote islands (20).

The substantially shorter chronologies may now resolve existing paradoxes or challenge alternative views about the prehistory of East Polynesia. For example, the earliest presence of sweet potato (*Ipomoea batatas*) in Mangaia, Cook Islands, dated to A.D. 1210–1400 and was regarded as a late occurrence (21), and similarly late dates on sweet potato from Hawaii (22) could now actually represent an initial introduction of sweet potato to these islands with colonization, and to East Polynesia more generally, regardless of whether Polynesians reached South America or Amerindians reached Polynesia (23). Conversely, linguistic similarity, often used to trace phylogenetic relationships of populations in East Polynesia according to a longstanding model of relatively slow, incremental expansion (24), now needs to be reconsidered in terms of specific founder effects and isolation, especially in the case of Rapa Nui. Similarly, the rise of monumental, ceremonial architecture within a much shorter regional chronology (25) implies a different kind of historical development as well as likely continuity with comparable structures in western Polynesia (12, 26). Finally, the remarkable artifact similarities documented in the "archaic East Polynesian" assemblages of the Societies, Marquesas, New Zealand, and other islands reflect homology of forms (e.g., in fishhooks, adzes, and ornaments) with late and rapid dispersals over the region

(27, 28). Indeed, similarities of form attributed to continuing interarchipelagic contacts may actually reflect sharing that occurred in mobility associated with colonization and not a later phase of long-distance interactions (29).

Later colonization also condenses the timeframes of human impacts on island ecosystems, particularly deforestation, and plant and animal extinctions. The remarkable speed of environmental transformations is now measured perhaps in decades rather than centuries and includes impacts on both terrestrial and marine biota caused by human hunting; predation by introduced animals such as the Polynesian rat (*Rattus exulans*), dog (*Canis familiaris*), and pig (*Sus scrofa*); as well as the human use of fire within the short occupational chronology that we propose. All of these demand major revision of previously held assumptions regarding the rate, causes, and consequences of extinctions with human impacts on pristine island ecosystems. For example, populations of at-risk species that are sensitive to predators introduced at the time of initial Polynesian colonization may be declining at much faster rates than previously believed (4, 30, 31). Abbreviating the duration of human settlement impacts by more than 50% on some islands makes a great difference to interpreting the decline of indigenous biota. Whereas these declines were thought to have occurred over a thousand years or more, it now appears that, in most cases, several hundred years was all it took. Furthermore, previously supported implications that there was a long period of relatively benign interaction among humans, rats, dogs, pigs, and indigenous vertebrates now need revision, as our refined model of colonization chronology suggests that impacts had to have been immediate, severe, and continuous.

Conclusions

Improvements in the reliability of radiocarbon dating, including greater rigor in the selection, identification and pretreatment of samples, together with a rapid increase in the total size of the radiocarbon date assemblage for East Polynesia, provide the conditions necessary for constructing a reliable model of the regional chronology of colonization. The model presented here has the advantages of a geographically wide coverage and a large sample of radiocarbon dates that was selected systematically by the elimination of poor quality and imprecise data. The results show that, after a relatively brief period of establishment in central East Polynesia, there was a remarkably rapid and extensive dispersal in the thirteenth century A.D. to the remaining uninhabited islands. This rate of human expansion is unprecedented in oceanic prehistory. Our model, although falsifiable, is likely to prove robust with further high precision radiocarbon dating of short-lived materials from those East Polynesian islands that currently lack secure chronologies based on such materials.

Materials and Methods

Radiocarbon dates from East Polynesia were sourced from published work and from dates provided by the authors (Table S1). We selected only radiocarbon dates in direct association with cultural materials or commensals from 300–3000 ^{14}C y BP. Several dates that were based on mixed materials (including soil) are problematic in terms of defining the source of carbon and were excluded from analysis. All radiocarbon dates were first categorized by the type of material submitted for dating (Table S1). Categories included short-lived plant/charcoal remains, twigs, seeds; identified long-lived plant/charcoal; unidentified charcoal; terrestrial bird eggshell; bone dates including fish, dog, human, turtle, etc; and marine shell (Fig. 2). These categories were then used to sort the 1,434 radiocarbon dates into one of two reliability classes (Table S1 and Fig. 3**)**. Class 1 dates included samples on short-lived plant remains (e.g., twig charcoal or wood, bark, seeds, leaves) and terrestrial avian eggshell, all of which have been shown to produce consistent and reliable ages in the Pacific relative to the target event, i.e., human activity (4, 6, 7, 32). Class 1 dates give the greatest chance of establishing an accurate age for recent colonization events. The remaining dates were placed into Class 2, as they are associated with unacceptably low levels of precision and/or accuracy for the task of defining relatively short colonization chronologies (i.e., samples with known or potential inbuilt age (including unidentified charcoal) (7); marine reservoir effect (33, 34); dietary, postdepositional or pretreatment contamination of bone (35–37); and imprecision associated with marine calibration (5, 38). Although many dates from unidentified charcoal and marine shell offer results consistent with Class 1 dates from the same contexts (15), their reliability cannot be established to the same extent. They might be "correct" dates, but without data on the longevity of the taxa dated, or the feeding habits of molluscs (e.g., deposit feeders), or unknown local ΔR marine reservoir effects, unquantifiable imprecision and inaccuracy of multidecadal to centennial-scale error can be added to the true age of a sample (33, 38, 39). Finally, we added a factor of 1 to Class 1 or 2 dates if the ^{14}C measurement error was >10% of their age (radiocarbon years before A.D. 1950), and/or if no local ΔR marine reservoir correction factor has been established for the region, which placed Class 1 dates into Class 2, and Class 2 dates into Class 3 (Fig. 3). Large SEs can be particularly problematic when trying to pinpoint the age of short colonization chronologies; for example, calibrating a conventional radiocarbon age (CRA) of 750 ± 30 y BP provides a 1 sigma calibrated age range of A.D. 1252–1283 (using INTCAL09: 40), whereas a CRA of 750 ± 80 y BP provides a wider window of possible ages from A.D. 1186 to 1382. This is exacerbated in the 13th century, where there is a substantial wiggle in the calibration curves (40) This process generated three overall reliability classes (Classes 1–3; Figs. 2 and 3 and Table S1), which formed the basis of our analyses.

Following the classification protocol, calibration probabilities were then calculated for the reliable Class 1 dates to derive an earliest and a latest estimate for the age of initial colonization on all East Polynesian island groups (Fig. 4). Cumulative probability curves provided the means of assessing our confidence that colonization occurred no later than a particular date (Fig. 4*A*). For the Society Island dates, this was set to A.D. 1200 based on the assumption that we have 100% confidence that colonization had occurred by this time; and for the remaining islands with Class 1 dates, this was set to A.D. 1300. Where the 50% cumulative probability point intersects the age axis (Fig. 4*A*) represents our LAEM, specifying, in years A.D., when it is more likely than chance that the actual colonization event occurred before this time. Our EAEM for initial colonization is based on the point at which the sum probability curves first show a steep rise due to the numbers of overlapping probability values from multiple dates.

We calibrated radiocarbon dates and generated age probability distributions from Calib rev 6.0.1 (41), using IntCal09 (40) for terrestrial samples from the Hawaiian and Line Islands; and SHCal04 (terrestrial) (42) for the remaining samples from the Southern Hemisphere, applying recommended ΔR marine reservoir correction factors where available (34). Where no ΔR exists, or is highly variable, no ΔR was applied (e.g., Auckland Islands). Marine samples were calibrated using the Marine09 calibration curve (40).

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