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Modeling the prehistoric arrival of the sweet potato in Polynesia

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Abstract

The sweet potato is a plant native to the Americas, and its pre-historic presence in Polynesia is a long-standing anthropological problem. Here we use computer-driven drift simulations to model the trajectories of vessels and seed pods departing from a segment of coast between Mexico and Chile. The experiments demonstrate that accidental drift voyages could have been the mechanism responsible for the pre-historic introduction of the sweet potato from the Americas to Polynesia. While present results do not relate to the feasibility of a transfer by purposeful navigation, they do indicate that this type of voyaging is not required in order to explain the introduction of the crop into Polynesia. The relatively high probability of occurrence and relatively short crossing times of trips from Northern Chile and Peru into the Marquesas, Tuamotu and Society groups are in agreement with the general consensus that this region encompasses the area of original arrival and subsequent dispersal of the sweet potato in Polynesia.

Keywords: Polynesia prehistory; Sweet potato; Computer simulation

1. Introduction

The sweet potato (*Ipomoea batatas*, Lam.) is a domesticated root plant that ranks as the fifth most important food crop in developing countries (Zhang et al., 2000). Wild varieties of sweet potato are not known to exist today. Vegetative reproduction, involving cuttings taken from the plant or the tuber, is the form of reproduction employed in areas of the world where it is cultivated, though sweet potato seeds have been collected across the plant's range in the Pacific and the Americas. It is unclear how readily the plant is able to reproduce from seeds without human intervention (Yen, 1960). It is generally accepted that the sweet potato is indigenous to the Americas, although there is some debate as to its exact center of origin. The oldest remains of domesticated sweet potatoes, dated to ~2000 B.C., come from Peru (O'Brien, 2000). A fossilized sweet potato tuber dated to 8080 ± 170 B.C. was found in Peru's Chilca Canyon region, but it is unclear if this specimen belonged to a wild or domesticated variety of the plant (Engel, 1970). Studies based on the plant's present day genetic variability suggest that Central America, and not Peru, was the most probable center of origin (Zhang et al., 2000). Yen (1974) discusses the further possibility of the independent evolution of the plant in Mexico and Peru but suggests that the single origin hypothesis may be preferable.

1.1. The sweet potato in Polynesia

The sweet potato is an important food crop in Polynesia (Hather and Kirch, 1991). It was initially thought that it had been introduced to the islands by the Spanish and Portuguese during the early 16th Century, but there is a significant amount of direct evidence which indicates the sweet potato had a prehistoric introduction into Polynesia. The oldest archaeological find is the carbonized remains of tubers from Mangaia Island in the Cook Islands of Central Polynesia, dated to A.D. ~1000–1100 (Green, 2005; Kirch, 2000). Sweet potato remains predating European contact have been recovered from Hawaii (A.D. 1290–1430), Easter Island (recovered from an

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earth oven dated to A.D. 1526 ± 100) and at a prehistoric site in New Zealand (Ladefoged et al., 2005; O'Brien, 2000). These finds demonstrate that the crop was not only present in Polynesia in prehistoric periods, but had dispersed throughout the region by the time of European contact.

1.1.1. Natural transport mechanisms

A series of mechanisms have been proposed to explain the prehistoric transfer of the sweet potato from the Americas to Polynesia. Bulmer (1966) investigated the propagation of different varieties of sweet potato in cultivation gardens in New Guinea, suggesting that dispersal can occur via birds that had ingested the plant's seed or traveled with seeds clinging to their bodies. According to Bulmer (1966), acid in a bird's stomach could cause scarification of the sweet potato's seeds which could help improve the chances of the plant's successful germination. Bulmer (1966) suggested that trans-Pacific transport could have been carried out by the Golden Plover, which is found throughout Polynesia and is known to visit the west coast of South America. While Bulmer believed it is plausible that birds are involved in helping to disperse different varieties of sweet potato between nearby cultivation areas, he concluded, on account of the large distances involved, that a bird introduction from South America was unlikely. Based on their Central American source region, Zhang et al. (2004) point to birds as possible transfer agents but do not suggest a particular species or group.

Sweet potato seeds are contained within spherical seed capsules about 1 cm in diameter. Each capsule holds one or two seeds. Unlike the plant's tubers and seeds, the capsules are buoyant. This led Purseglove (1965) to propose that the plant may have been introduced into Polynesia by capsules that had drifted across the Pacific. Sauer (1993) argued that it is unlikely that seed capsules could survive for long in the surf zone along a beach, but that the plant's seeds could have established themselves in a tidal estuary or have been collected by Polynesian islanders. We could find no information on how capsule contact with salt or fresh water might affect seed viability and are unable to estimate how long a capsule could remain afloat and still produce viable seeds. Additionally, sweet potato seeds, seed pods or tubers could have rafted to Polynesia on mats of floating debris.

1.1.2. Human mediated transport mechanisms

While uncertainties remain, there seems to be a growing consensus that the transfer from South America into Polynesia was performed by humans (see the Ballard et al., 2005 compilation). One of the arguments supporting this position is the similarity between the word for sweet potato in many Polynesian languages and *cumal* or *cumar*, words for the sweet potato found in dictionaries of Chinchasuyo, a regional dialect of Quechua, a language originating in Peru (Brand, 1971). According to O'Brien (1972) the term for sweet potato in the Polynesian languages can be reconstructed to the Proto-Polynesian word *kumala*. Yen (1974) presents a list of similar sounding words for the plant found in languages from Peru, Ecuador and Colombia. Brand (1971) argues there is no evidence for the use of the word *cumal* anywhere along the coast of Ecuador or Peru, but Scaglion (2005) suggests that the term *comal* or *cumal* was used by the Cañari people of Ecuador whose territory, prior to European contact, likely included sections of the Ecuadorian coastline along the Gulf of Guayaquil.

According to Green (2005), the sweet potato could have been introduced to the islands by Polynesian voyagers who sailed across the Pacific to the New World, retrieved the plant and returned to Polynesia. That the sweet potato was transported into Polynesia while other important South American crops were not is seen by some as an indication that the transfer was performed by Polynesians and not South American travelers (Ballard, 2005; Green, 2005). The argument is that South American voyagers would have also stocked their vessels with staples such as maize or *Phaseolus* beans. Polynesians sailors, on the other hand, would have associated the sweet potato with yam (Leach, 2005), a crop they were familiar with, and would have preferred to include it in their stores while leaving maize and other unfamiliar food sources behind.

Alternatively, travelers from South or Central America could have (deliberately or accidentally) reached Polynesia in boats carrying the sweet potato. Among the different watercraft used along the west coast of South America prior to Spanish contact, the most capable of withstanding a journey to Polynesia were probably the balsa log sailing rafts from the area that today encompasses Ecuador and Northern Peru. Based on reports by early Spanish visitors, Edwards (1965) concludes that these "…were evidently designed for lengthy voyages and large cargoes. They were provided with huts for shelter and frameworks or bulwarks to contain the cargo." One early Spanish account describes a raft capable of carrying 50 men and three horses, another states that the observed raft could hold 30 large casks (Edwards, 1965). Anecdotal reports indicate that these rafts were in use as far south as Lima (~12° S) and guares or steering foils associated with these vessels have been unearthed at a site in Ica (~14° S) dating to circa 300 B.C. Later reports suggest that the rafts were used for long-distance trade voyages even as far as from Lima to the Gulf of Panama (Edwards, 1965; McGrail, 2001). Scaglion (2005) notes that the distribution of these sailing rafts is thought to have been concentrated in the Gulf of Guyaquil region, which has been mentioned above in connection with the Cañari people. Smaller vessels (including log, bundle and hide float rafts as well as dugout canoes) were used for fishing and transport on rivers and coastal areas of Chile, Peru, Ecuador, Colombia, Panama and Mexico (McGrail, 2001).

By sailing the Kon-Tiki from Peru to the Tuamotu Archipelago, Thor Heyerdahl's expedition demonstrated that a balsa wood raft based on traditional South American designs could survive a crossing into Polynesia (Heyerdahl, 1952). Pottery found in archaeological sites in the Galápagos Islands correlate with the pottery complexes from several different time periods in Peruvian and Ecuadorian prehistory, suggesting that the islands had been visited by several different groups of South Americans in pre-contact times, further demonstrating that the peoples of this region were capable of long distance ocean voyages (Heyerdahl and Skjölsvold, 1956).

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It is worth noting that any crew (Polynesian or American) need not have survived the voyage from the New World into Polynesia. The sweet potato could have established itself on an uninhabited island if the tubers were washed ashore. Also, if the boat reached the coast of an inhabited island, the people living on the island could have happened upon it and planted the sweet potato themselves (O'Brien, 1972).

1.1.3. Areas, sources and timing of initial introduction

Based on anatomic variation between sweet potato populations, Yen (1974) proposed three main introduction paths for the crop into Oceania: a prehistoric transfer from South America to Polynesia, transport by the Spanish from Mexico to the Philippines and an introduction from Europe to the East Indies and Papua New Guinea. Yen (1974) suggested that the most likely area for prehistoric introduction lay in a "central ellipse region" encompassing the Marquesas, Cook and Society Islands. However, as specimens from Hawaii and Central America were not analyzed in his study, he cautioned that his results could not be used to rule out a possible introduction from Mexico to Hawaii.

Green's (2005) two-way trip hypothesis agrees with Yen's main conclusions, but further restraints the potential arrival sites within the central ellipse and also goes on to add an initial crossing from Polynesia to South America. Green (2005) proposed that Polynesian voyagers from Easter Island or the Mangareva–Temoe–Pitcairn region made their way to South America and reached the Gulf of Guayaquil area, where they acquired the sweet potato. These voyagers then sailed back toward Polynesia but, instead of returning to their original departure site, made landfall somewhere in the area limited by Mangaia Island in the southwest and the Marquesas in the northeast, including the Society Islands and the Tuamotu Archipelago. According to Green (2005), an introduction in this area is more likely, since the islands in this region form a screen within which it would be hard to avoid sighting land and also because there were substantial interactions between the islands in this group in prehistoric times.

The two proposed American source regions from which the plant could have been introduced into Polynesia coincide with the suggested centers of origin mentioned earlier. The linguistic findings linking the Polynesian terms for sweet potato to Quechua and the languages of the Cañari people point to northwest South America as the source for the plant. On the other hand, genetic analyses of specimens from present day cultivars, conducted by Zhang et al. (2004), indicate that Central America was the region from which the Oceanic sweet potato originated. However, these analyses have been criticized (Green, 2005; Scaglion, 2005) for being based on the contemporary distribution of the sweet potato and hence failing to account for the multiple introductions of the sweet potato into Oceania following Yen's tripartite hypothesis. In the case of New Zealand at least, there are indications that the genetic makeup of prehistoric and post-contact sweet potato cultivars are different from each other (Harvey et al., 1997).

Jones and Klar (2005) argue that sewn-plank canoes and fishhooks from prehistoric sites in Channel Islands off the coast of Southern California are similar to the ones used in Polynesia. Additionally, three words used to refer to boats by the Chumashan and Gabrielino speakers of the southern California coast are similar to Proto-Central Eastern Polynesian terms pertaining to canoe construction, suggesting to the authors that there may have been contact between Polynesians and the peoples of this region at some point in prehistory. The prehistoric range of the sweet potato did not extend to Southern California. If such contact was responsible for the transport of the sweet potato, voyagers would have to have sailed south along the coast, collecting the sweet potato from Mexico or Central America before crossing into Polynesia. This hypothesis would be in agreement with a Central American source for pre-contact Polynesian sweet potato.

Establishing a time frame for the introduction of the sweet potato is challenging and in many cases depends upon the interpretation of secondary evidence, since dated sweet potato remains from Polynesia are scarce. It is known that the plant was present in Mangaia, the southernmost of the Cook Islands, at around A.D. 1000 (Kirch, 2000). O'Brien (1972) suggested, on the basis of linguistic evidence, that the sweet potato could have arrived in Polynesia as early as the migration into Samoa, but was certainly present by the dispersal out of the Marquesas. Colonization of central-eastern Polynesia, including the Marquesas, is thought to have resulted from a dispersal out of Tonga and Samoa. Radiocarbon dates from the Marqueas are inconsistent, making it difficult to pinpoint the date of initial settlement. Kirch (2000) suggests that the expansion out of Tonga and Samoa had begun by A.D. 1 at the latest, but Hunt and Lipo (2006) argue that this expansion did not occur until after A.D. 800, followed by rapid colonization of eastern Polynesia, including the Marquesas.

Ballard (2005) proposed a much more narrow timeframe for the introduction of the sweet potato. He suggests that the plant was introduced after the initial colonization of Hawaii and Easter Island but prior to the colonization of New Zealand. This would imply that the introduction occurred not much earlier than A.D. 1000 or much later than A.D. 1150.

1.2. Prehistoric introductions of other South American plants

While our experiments that follow were designed and analyzed having in mind only the introduction of the sweet potato, the results are potentially relevant to other American plant species which produce buoyant fruits or seeds or which could have been transported into Polynesia by prehistoric voyagers.

One of them is the calabash or bottle gourd (*Lagenaria siceraria*), a plant with edible fruit that can also be dried to produce containers. Archaeological remains indicate that the plant was present in the Americas by at least 9,900 B.C. Its prehistoric range along the American west coast is thought to extend from California to Northern Chile. By 7000 B.P. the plant had been domesticated in China and Japan. By A.D. 1200, the bottle gourd had been dispersed throughout eastern Polynesia and to the most distant points of the Polynesian triangle (Clarke et al., 2006). Recent comparison of

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genetic markers, in agreement with earlier morphological analyses, shows that the present day Polynesian population received significant genetic contributions from both Asian and American subspecies of the plant, supporting a dual-origin hypothesis for the bottle gourd in Polynesia (Clarke et al., 2006). The plant's fruit is buoyant and specimens that floated in salt water for 224 days still retained viable seeds (Whitaker and Carter, 1954).

Another plant that could have floated or been transported by humans into Polynesia is the soapberry (*Sapindus saponaria*), whose seed-containing berries may be crushed to produce a natural detergent. Its present-day range along the west coast of the Americas extends from Mexico to South America. Its extent in prehistoric times is unclear, although its remains have been identified at prehistoric sites in Peru dating from 2500 to 3000 B.P. (Langdon, 1996). There is no direct archaeological evidence for the presence of the soapberry in pre-contact Polynesia but written descriptions of the plant from early European explorers have been interpreted as an indication that the plant could have reach the islands in prehistory (Green, 2005; Langdon, 1996). Dried soapberries form an air-filled seed-containing cavity which can float and the seeds themselves are capable of floating (Degener, 1945).

Unlike the sweet potato, where the linguistic *kumara*-connection hints at the possibility of contact between Polynesia and the Americas, we are unaware of any similarity between the Polynesian and American words for bottle gourd and soapberry.

2. Methods and data

Computer simulations are conducted to investigate two of the proposed transfer theories:

1. Accidental drift voyage by vessels from the Americas
2. Seed capsule drift

The goal is to provide spatial and temporal constraints to each of these two possible types of transfer. That is, assuming a particular type of transfer occurred, results from the simulations are used to provide information, for example, on likely departure and arrival areas.

The introduction of the sweet potato by deliberate voyages, be it a single crossing from the Americas or a round trip starting in Polynesia, is not modeled. We do not claim these events would be less likely than the ones we simulate. Still, given the lack of direct information on prehistoric American and Polynesian navigational abilities and strategies, as well as the difficulties and arbitrariness associated with simulating deliberate navigation, we believe drift-only experiments provide more useful results at this point. For similar reasons, we do not attempt to model a possible introduction by birds.

The experiments consist of positioning drifters along the Pacific coastline of South and Central America and then recording their movement under the influence of winds and currents. Two types of drifters are used: vessels and seed capsules. In the vessel simulations, displacement is a function of winds and currents. For the seed capsule simulations, movement is determined by ocean currents only. The seed capsule drift simulations may be interpreted as representing the trajectories of floating seed capsules or capsules rafted on top of a mat of floating debris.

2.1. Input data

The ocean current values used in both vessel and seed capsule drift simulations come from the Estimating the Circulation and Climate of the Ocean (ECCO) experiment. These are estimates in which output from the Massachusetts Institute of Technology General Circulation Model (MITgcm) are constrained by observed variables such as climatological water density and sea surface height. The resulting currents are, consequently, a blend of modeled and measured data (Stammer et al., 2002).

The ECCO data set consists of 10-day velocity averages spanning the period between January 1993 and November 2005. Velocities are spatially distributed in a collection of 3-dimensional bins with varying horizontal and vertical lengths. From the equator to ±11°, the horizontal dimensions are 0.3° of latitude by 1° of longitude. Dimensions change to 0.5° × 1° between ±12° and ±20° and go to 1° × 1° for latitudes polarward of ±20° (near the equator 1° is approximately 111 km). The chosen values represent an average of the first 5 m of the water column within each bin.

The MITgcm is forced by winds from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR). These same winds are used as input in the vessel drift simulations. The NCAR/NCEP reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado. The original wind data are daily means covering the same period as the currents with 1.9° × 2° horizontal resolution. For the simulations, the wind data are interpolated to the current field spatial resolution.

2.2. Experiment design

Departure bins are defined as data bins that have at least one side touching the continents of South and Central America between the latitudes of −50° S and 30° N. At the start of the simulation, a drifter is positioned at the center of each departure bin. The distance from the center of any bin to the coast is never larger than 0.5°. This means that, at departure, the maximum distance from shore varies from ∼35.5 km to ∼55.5 km.

Given the change in bin size with latitude, the concentration of drifters departing from a specific segment of the coast varies from approximately one departure per degree of latitude in the outer limits of the domain to three departures per degree of latitude near the Equator. In total, 160 drifters are "set loose" along the coast at the beginning of every simulation. Simulations are started every 15 days for 12 years, from 1993 to 2005.

The displacement of every drifter is recorded individually. If a drifter enters the target area around one of the pre-selected

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Table 1
Target areas' latitude and longitude (in degrees) representing the centre of the target areas used in the experiments

Target	Lat	Lon	RTs	Target	Lat	Lon	RTs
Galapagos	−0.5	268.9	T_2	Kiritimati	1.75	202.2	T_1
Easter	−27.2	250.5	$T_{0.5}$	Phoenix	−3.8	188.4	T_2
Pitcairn	−25.2	229.8	$T_{0.5}$	Samoa	−13.9	187.8	T_2
Mangareva	−23.2	224.9	$T_{0.5}$	Tokelau	−9	188.5	T_2
Marquesas	−9	220	T_2	Tonga	−20	185	T_4
Tuamotu	−16	215	T_4	Tuvalu	−7.8	178	T_4
Rapa	−27.7	215.5	$T_{0.5}$	Fiji	−17.5	178.5	T_4
Australs	−23.5	210.5	$T_{0.5}$	Kiribati	−0.7	174	T_4
Society	−17.8	210.2	T_2	Marshall	9.2	168	T_4
Hawaii	20.5	202.5	T_{h1}	Vanuatu	−16	167.6	T_6
Cooks	−20.2	202	T_2	N. Zealand	−41	174	T_{nz}
Tabuaeran	3.75	200.2	$T_{0.5}$				

Southern hemisphere latitudes are negative. RTs, relevant target size (see Table 2 for target sizes).

islands and island groups (Table 1) it generates a "hit". In a given simulation, each drifter can only hit a specific target once and no hit is recorded when a drifter re-enters a previously visited target area. There are no landings, which means that drifters do not feel the presence of the islands and can hit more than one target within the same simulation.

For most islands, five target dimensions, ranging from 0.5° × 0.5° to 6° × 6° are considered. Different target areas are used in the case of Hawaii and New Zealand (Table 2). One of the reasons for adopting targets of varying sizes is the uncertainty in vessel position due to errors intrinsic to the drift simulation. Another reason is the need to take into account the fact that many of the selected targets do not stand alone in the ocean, but are in fact surrounded by other islands. The hits on the larger target sizes can be interpreted not as arrivals at a specific island, but at an island group, or at least at the central portion of an island group. A series of maps centered on the coordinates listed in Table 1 and containing the adopted target sizes were generated so that, by visual inspection of target sizes in relation to the spatial distribution of land, a relevant target size is selected for each island/archipelago present in the simulation (Table 1). Examples of the maps used for relevant target size selection are shown in Fig. 1.

Given the variation in data bin size with latitude, the number of hits on a specific target must be corrected in order to compensate for the disparity in departure density. A single simulated hit is counted as one if its drift originated in the higher latitudes of the domain; as half a hit if the departure area was in the intermediate latitudes and only as one third of a hit if the drift started in the equatorial region.

Table 2
Dimension, in degrees, of target areas used in the experiments

Target	Lat × Lon	Target	Lat × Lon
$T_{0.5}$	0.5 × 0.5	T_6	6 × 6
T_1	1 × 1	T_{h1}	4 × 5
T_2	2 × 2	T_{h2}	5 × 6
T_4	4 × 4	T_{nz}	12 × 12

$T_{0.5}$–T_6 are adopted for all islands with the exception of Hawaii, where T_{h1} and T_{h2} are used, and New Zealand, with target area T_{nz}.

2.2.1. Vessel drift simulations

Estimates of vessel displacement are based on the United States Coast Guard (USCG) Leeway Drift Method. This empirical scheme has been adopted by the USCG for its search and rescue missions (Allen, 1996; USCG, 2002). The method assumes one component of displacement is directly determined by the currents; boats move with the same speed and direction as the water. The wind generated boat speed is only a fraction of the original wind value. Vessels do not drift in the same direction as the wind but at an angle, either to the right or to the left. Both speed adjustments and deflection angles have been experimentally determined by the USCG and are dependent on boat type. The present simulations make use of a boat type that most closely resembles a large canoe with rudimentary canopy (Arthur Allen, personal communication, 2004). The effects of storms and waves are not taken into consideration and boats do not sink.

This method, using the same current and wind input data, has satisfactorily reproduced vessel drift in the Atlantic. See Montenegro et al. (2006) for a more detailed description of the methodology.

The experiments last for 180 days, with wind, current and vessel position being updated every 2 days. The 180 day length is chosen based on the upper limit of long historically recorded drift voyages (Callaghan, 2003a; Kohl, 1982; Levison et al., 1973). The 2 day temporal resolution is used to minimize the undesirable occurrence of displacements that are larger than the dimensions of the input data bins. If this occurred, boats would have moved over a large section of the ocean without being influenced by local flow conditions.

2.2.2. Seed capsule drift simulations

The seed capsule experiments last 365 days, with current values and capsule position updated every 5 days. Capsules move with the same velocity as the water. The 5 day interval is adopted because, being influenced only by the currents, the seed capsules move more slowly than the boats. As we are not aware of how long the seeds inside a capsule will remain viable, nor how long seed pods can remain buoyant in salt water, the arbitrary year-long duration of the drift might be much longer or much shorter than the actual seed viability. If viability is lost

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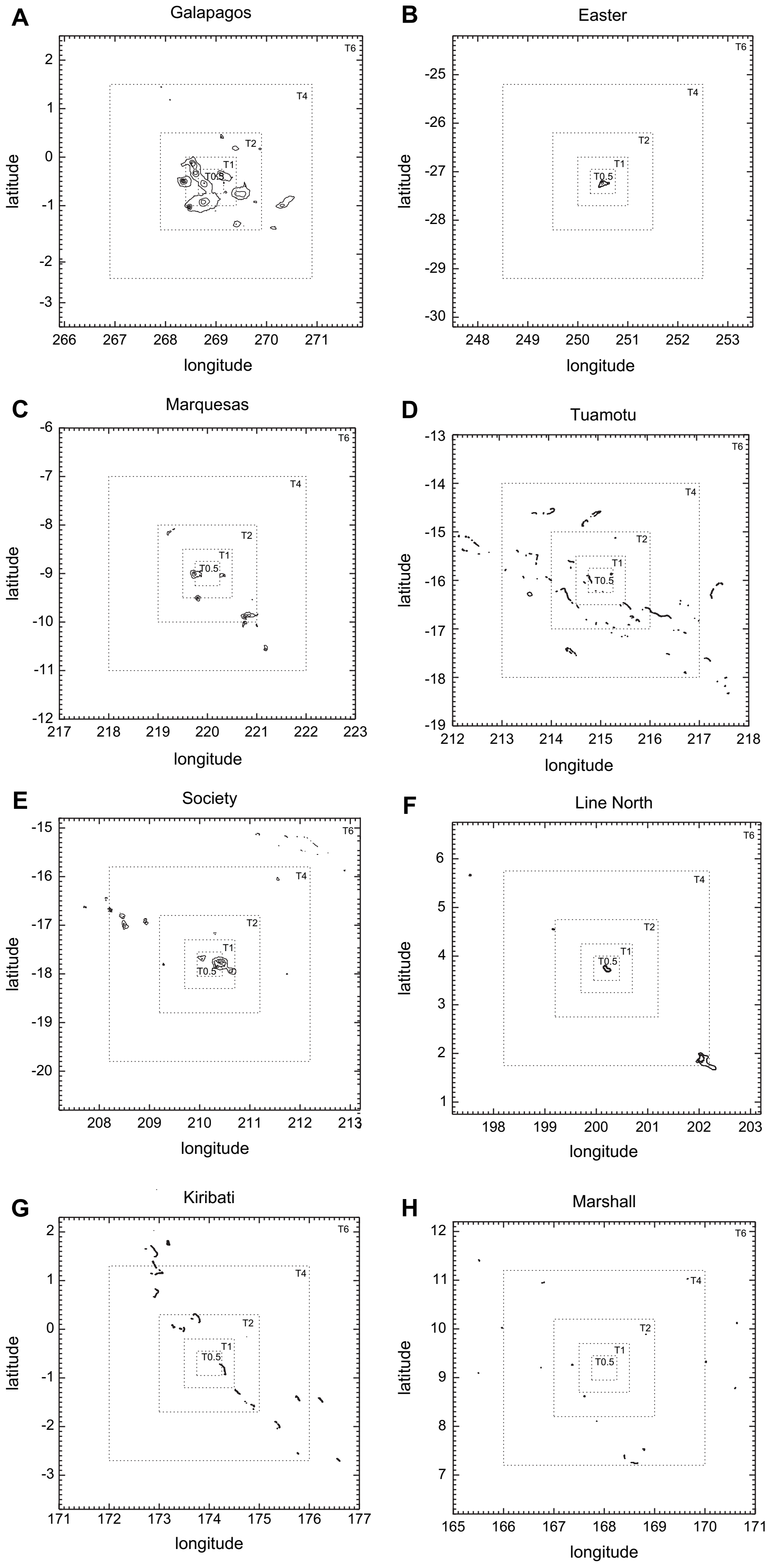

Fig. 1. Example of target sizes (dashed lines) in relation to land distribution. (A) Galapagos; (B) Ester; (C) Marquesas; (D) Tuamotu; (E) Society; (F) Tabuaeran; (G) Kiribati; (H) Marshall. The figure's axes represent the T_6 target box.

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before 360 days our results are still useful. This follows since time of arrival at each target is known, and hence, one would only need to discard the hits that occur after the seeds lost their viability. If, on the other hand, seeds are capable of germinating after periods longer than a year, our results would provide an incomplete set of potential arrival and departure areas.

In controlled experiments with the coconut (*Cocos nucifera*, which is thought to have dispersed by ocean drift), no seeds germinated after more than 110 days floating in seawater, but there are indications that some coconuts could remain viable for periods of about 140 days (Ward and Brookfield, 1992). Taking these values into consideration, we believe the duration of our experiments cover and most likely largely exceeds, the period during which sweet potato seeds would retain their viability in the ocean.

2.3. Previous voyaging simulations in Polynesia and the West Coast of the Americas

A sophisticated ocean voyage simulation model was developed by Levison et al. (1973) in their landmark study of the settlement of Polynesia. The method was later adopted by Irwin et al. (1990) and Irwin (1992) for testing the efficiency of different navigation strategies in the settlement of Polynesia. It was also used by Callaghan (2003), with slight modifications, for the study of prehistoric trade between Ecuador and Mexico.

In all these simulations, vessel movement is influenced by winds and currents that, instead of being deterministically calculated by a numerical model, are probabilistically defined based on local mean observations. The probabilistic method allows researchers to conduct a large number of simulations which will, assuming the statistical behavior of the flow is adequately captured by observations, generate a robust description of possible voyages. It follows that no matter how many simulations are carried out the method will perform badly in inadequately sampled areas. Independent of input data quality, the method does not take into account the temporal and spatial autocorrelation of the oceanic and atmospheric flows. The correlation between local winds and currents is also absent. These weaknesses were already recognized by Levison et al. (1973).

Our input data provide a dynamically coherent, more realistic description of ocean and atmosphere flows where not only the mean state but also a significant portion of the system's variability is present. On the other hand, by using currents and winds from data corrected numerical models, we have a limit on the number of drift simulations that can be carried out.

Another relevant difference is that vessel occupants in the Levison et al. (1973) simulations are lost, but are still capable of controlling their boats, which move as if being sailed downwind. Our simulations assume occupants have lost the ability of controlling their boats; vessels are pushed by the wind but are not sailed.

3. Results

A graphical representation of the simulation output is given in Fig. 2, which shows tracks of the drifters, both vessels and seed capsules, that hit targets of size $T_{0.5}$ (for Hawaii, T_{h1}) in the second quarter experiment (drifts that started between the months of April and June). As seen in Fig. 2, drifts that hit a particular target tend to originate from continuous segments of the departing coast. Some targets are hit from 2 distinct segments, one in the northern and one in the southern hemisphere. All vessels that hit the Marquesas in the T_2 experiments, for example, started their drift along the portion of the coast between 5° and 33° south or from the segment between 21° and 23° north (Table 3).

This feature of simulated drifts is used to estimate the probability of occurrence for each crossing. This is done by dividing the number of hits on a particular target by the total number of drifts initiated along the portion of the coast from which the hits originated. The probabilities of occurrence can be used to compare different crossings and can also provide insight on the feasibility of a particular path. Still, they should be interpreted with care, as the method for calculating them penalize to some extent crossings that originate over larger sections of the coastline. In fact, if a larger area of the coast is "available" to a particular crossing this would increase the chance of it occurring, albeit in a way the present data is not able to quantify.

Only results regarding crossings that hit the relevant size targets are presented and discussed in detail. Tables containing the probability of occurrence, average crossing time and average departure latitude for hits in all target sizes are provided in Appendix A.

3.1. Vessel simulations

Of the 23 available targets, 19 are hit in the vessel experiments (Table 3). Of these, 16 are hit with at least 1% probability and 8 are hit with probability of 2% or more. When a target is hit from two distinct coastal segments, hits from one of these segments are usually much more probable than hits from the other.

The fastest (8 days) and second most probable (9.9%) crossing is from Ecuador and Peru to the Galapagos. The most probable crossing is the one from Central America and Mexico to the Marshall Islands (11.45%). Within the "central ellipse" region (Green, 2005; Yen, 1974), relatively high hit percentages are seen for trajectories from Peru and Chile to the Tuamotu group (7.41%), the Marquesas (5.68%) and the Society Islands (2.43%). Minimum travel times for the three previous targets vary from 90 to 126 days, the Marquesas crossings being fastest. Crossings from northern Mexico into Hawaii are among the fastest (80 days) and have comparatively high probability of occurrence (2.87%).

3.2. Seed capsules simulations

Seven island groups are hit in the seed capsule simulations, 3 of these with more than 1% probability (Table 4). The most probable (17.2%) and fastest (15 days) crossings by far are the ones from Central America, Colombian and Ecuador into the

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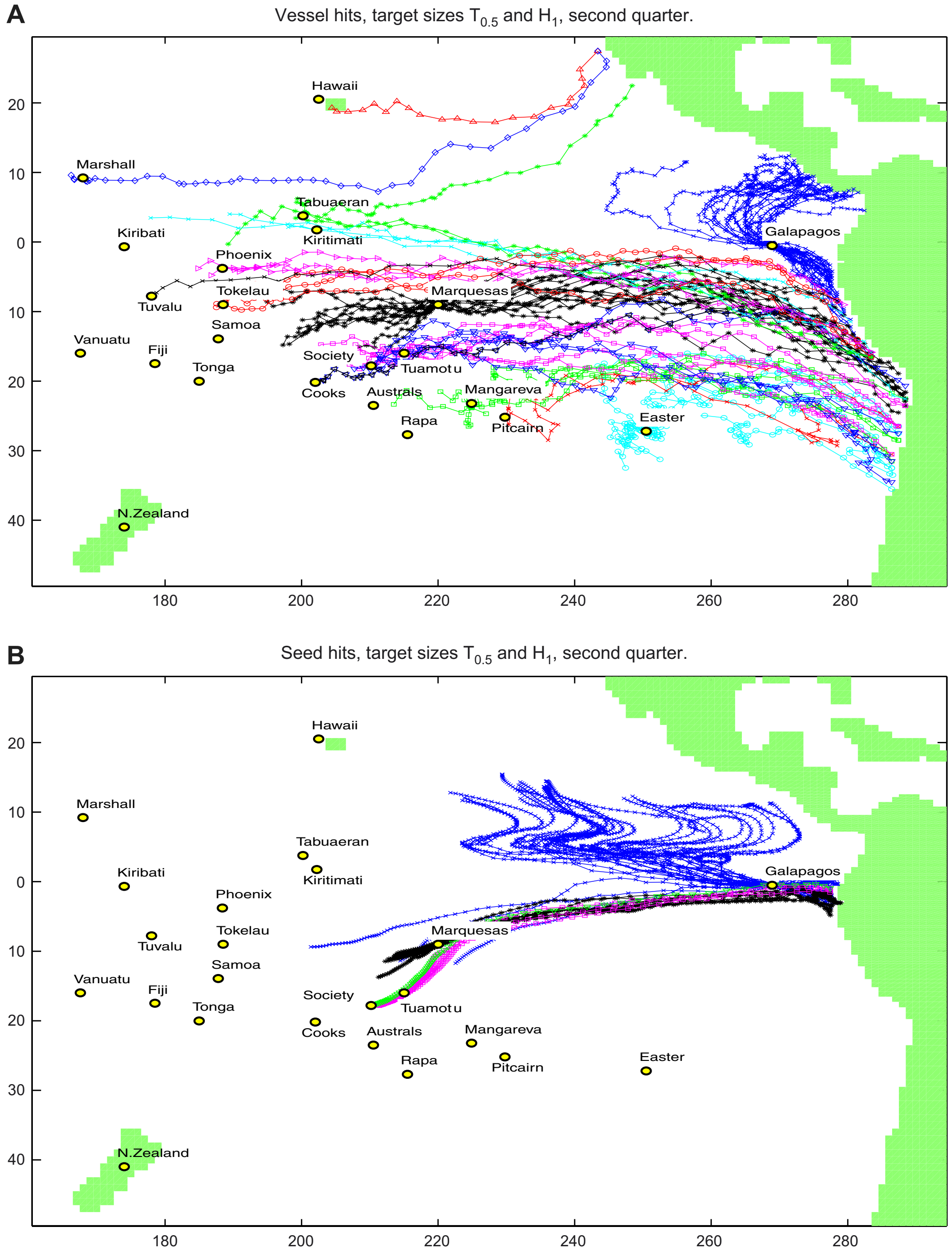

Fig. 2. Example of simulation results. Top: Track of the vessels that hit targets of size $T_{0.5}$ in the second quarter experiment. Colors refer to the island where the hit occurred. Bottom: As for top panel for the seed capsule drift simulation.

Galapagos. Hits to the Tuamotu group (1.95%) and the Marquesas (2.68%) are relatively probable with fastest crossings ranging from 165 to 120 days respectively. The departure area for the Tuamotu and Marquesas crossings is restricted to Ecuador.

4. Discussion

Our experiments were designed to model vessel and seed capsule displacement over time. Vessel and seed survivability at sea were only indirectly considered by controlling drift duration. No attempt was made to model the very complex series of events pertaining to the actual colonization (or cultivation) of the sweet potato once it arrives at an island. Our experiments provide spatial and temporal constraints for each of the two analyzed introduction processes, assuming these processes occurred. That is, the main goal of our study is to provide likely source areas, islands of first arrival and expected travel time for both modes of introduction.

The probability of occurrence values permits some speculation about the feasibility of each crossing, but interpreting them is challenging. The difficulty arises in objectively

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Table 3
Crossing parameters for vessel hits on relevant target sizes

Target	Hits	%	AveT	MinT	AveL	MinL/MaxL
Galapagos S	523.6	9.88%	27	8	−8.51	0/−24
Easter	46.0	1.37%	91	56	−33.00	−43/−26
Pitcairn	23.0	1.77%	125	98	−31.48	−37/−27
Mangareva	32.5	0.95%	129	104	−30.26	−39/−17
Marquesas N	2.0	0.23%	131	100	22.00	21/23
Marquesas S	411.2	5.68%	128	90	−19.84	−33/−5
Tuamotu N	3.0	1.04%	135	90	22.00	22/22
Tuamotu S	440.0	7.41%	145	112	−25.97	−36/−13
Rapa	1.0	0.35%	154	154	−30.00	−30/−30
Australs	2.0	0.14%	143	136	−30.00	−32/−28
Society S	124.5	2.43%	154	126	−26.18	−35/−13
Hawaii	23.0	2.87%	101	80	25.96	22/27
Cooks	3.5	0.41%	161	144	−23.86	−33/−14
Tabuaeran N	84.5	3.04%	128	68	19.69	9/27
Tabuaeran S	8.3	0.56%	149	126	−15.48	−22/−6
Kiritimati N	56.2	1.33%	130	76	18.56	10/27
Kiritimati S	21.2	0.62%	144	120	−17.76	−26/−6
Phoenix N	21.0	1.04%	141	98	22.93	16/26
Phoenix S	59.8	1.30%	163	138	−13.57	−28/−3
Samoa S	0.8	0.29%	156	142	−12.61	−15/−9
Tokelau N	17.0	1.69%	145	100	24.82	22/27
Tokelau S	27.0	0.78%	163	142	−13.98	−26/−6
Tuvalu N	19.0	1.16%	140	106	23.50	19/27
Tuvalu S	5.3	0.40%	168	158	−11.73	−17/−3
Kiribati N	143.5	4.98%	142	100	23.32	14/27
Kiribati S	13.2	0.43%	168	150	−16.05	−26/−8
Marshall	233.0	11.45%	151	108	24.83	12/27

Hits, number of hits compensated for differences in departure density; %, probability of occurrence; AveT, average crossing time; MinT, minimum crossing time; AveL, average departure latitude; MaxL/MinL, range of departure latitude. The N and S following some targets indicate northern of southern departure area trajectory.

defining a threshold percentage above which a crossing could be classified as likely. Some insight is gained be evaluating introduction scenarios based on the probabilities and then deciding if these seem plausible.

Take, for example, the vessel hits on the Marquesas, which have a 5.68% probability of occurrence. Which scenarios could validate this introduction path? The 5.68% value is based on a departure area extending approximately 3700 km along the coast of South America between 5° and 33° south. Suppose one boat containing sweet potato tubers drifted out to sea every year from this segment of the coast. This means that about 5 vessels which had remained at sea for no more than 180 days (average of 128 days) would reach an area of approximately 200 × 200 km centered on the main islands of the Marquesas every 100 years. Assume the sweet potato to be established in South America by 4000 BP and that it had arrived in Polynesia by 2000 BP. This would provide 2000 years, or about 100 potential introduction events. The same kind of projection for the Marquesas T_1 hits (with 2.73% probability of occurrence, see Appendix A) point to about 54 potential introduction events.

Table 4
Crossing parameters for seed hits on relevant target sizes

Target	Hits	%	AveT	MinT	AveL	MinL/MaxL
Galapagos	594.2	17.42%	50	15	−0.81	−5/17
Marquesas	40.9	2.68%	209	120	−2.84	−6/0
Tuamotu	20.8	1.95%	260	165	−2.60	−5/0
Society	0.7	0.23%	248	225	−1.00	−1/−1
Hawaii	0.3	0.11%	370	370	−3.00	−3/−3
Tokelau	0.7	0.23%	250	215	−2.00	−2/−2
Tuvalu	0.3	0.11%	285	285	−1.00	−1/−1

Column names are the same as in Table 3.

The dates for the presence of the crop in South America and its arrival in Polynesia are conservative estimates and the period available for the transfer could be much longer than 2000 years. While the rate of vessel departure is arbitrary, our opinion is that it is not unreasonable.

As survival of vessel and crew at sea is not considered, this very simple speculative exercise provides the upper limit to potential introduction events. Still, at least from the point of view of transport from South America, we believe that the vessel crossings with higher probabilities of occurrence should be considered plausible mechanisms by which the sweet potato arrived in Polynesia. In our opinion, similar speculation on the number of potential introductions by seed drift must wait until more data is available on the seed's tolerance to the ocean environment.

4.1. Vessel drift

Below we briefly discuss how the vessel drift results relate to particular aspects of some existing theories on the introduction of the sweet potato as well as present some of our own.

4.1.1. Arrival within the central ellipse area

Within the central ellipse area (Green, 2005; Yen, 1974), the Tuamotu, Marquesas and Society groups present much higher probability of occurrence than the other islands. In fact, the Tuamotu and Marquesas hits present, respectively, the second and third highest probabilities of all Polynesian targets. Crossings into these two groups are also among the fastest, with crossings into the Marquesas being slightly faster than into the Tuamotu group (Table 3).

Compared to other targets in the area, hits into the Marquesas can originate from a larger section of the South American coast. The Marquesas crossings also tend to start more to the north, within the known range of balsa log sailing rafts. Assuming this was the type of vessel responsible for the transfer and that the source area was the Gulf of Guayaquil region (Scaglion, 2005), the Marquesas would appear to be the more likely arrival area within the central ellipse.

4.1.2. Central America and Mexico as source regions

According to our results, a prehistoric introduction of the sweet potato from Central America would most likely result

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in arrival at Hawaii. Other targets are hit from this section of the coast (notably the Marshall and Kiribati archipelagos) but Hawaii is the only one among them where the sweet potato is believed to have arrived before European contact (Green, 2005).

The Hawaiian archipelago was settled in the later stages of the Polynesian colonization process and does not appear to be a center of dispersal into other areas (Hurles et al., 2003; Kirch, 2000). Even if accidental drifts did bring the sweet potato to the region, it is unlikely that this would have been the original introduction site. While probably not related to the sweet potato, it is still interesting to note that accidental drifts from northern Mexico to Hawaii and other areas provide pathways for the suggested contacts between southern California and Polynesia (Jones and Klar, 2005).

4.1.3. Multiple introductions

Anatomic variability of the plant within the central ellipse area has been raised as a possible indication of multiple prehistoric introductions (Green, 2005). The large number of targets hit and the probability of occurrence of many of the crossings indicate that vessel drifts provide many access routes from South America into Polynesia and that such mechanism could be associated with multiple introductions of the sweet potato into the region.

4.1.4. Drifts as information conduits

Accidental drifts from South America could have informed Polynesians of the existence of a land to the East, even if no South American occupants survived the journey. From this perspective, accidental drifts might have played a role in a two-way trip from Polynesia to South America and back. Easter Island, Pitcairn and Mangareva, listed as likely starting points for such a trip (Green, 2005), are hit with about the same probability (between 2% and 1%), but crossings into Easter Island tend to be significantly shorter.

Recent radiocarbon dates for the initial settlement of Easter Island suggest that it was colonized at about A.D. 1200 (Hunt and Lipo, 2006), at a time the sweet potato was already present in Mangaia (Kirch, 2000). If this was the case, while Easter Island could still have acted as a launching site for a two-way journey, this could not have been the original introduction path, nor could Easter Island have been the original arrival site.

4.1.5. Absence of maize as indication of Polynesian mediated transfer

On possible flaw with this argument is that the exclusion of maize and other crops might have occurred after arrival and not before departure. That is, vessels arrived in Polynesia from South America carrying a variety of staples, but only the sweet potato was successfully adopted and cultivated due to its similarity to yam.

If transfer occurred via accidental drift no inferences can be made about what was being transported, but there is no reason to expect that South America vessels routinely sailed carrying a representative array of locally important food sources.

4.1.6. Comparison to previous studies

In contrast to our results, no accidental drift that started along the coast of South America reached Polynesia in the experiments of Levison et al. (1973). This led the authors to conclude that contact between the Americas and Polynesia could only occur via intentional voyages. Part of this disparity is due to differences between our method and the one adopted by Levison et al. (1973) that have already been listed above. Still, this large dissimilarity in results is most likely explained by the different number of departing points along the American coast. In our experiments boats depart from 160 different points, while in the Levison et al. (1973) simulations have six departure points.

Our results indicate that hits to a particular island group originate on specific segments of the coast. Furthermore, some portions of the coast, like the interval between 9° N and 3° S, produce no Polynesian hits. We believe that the much larger spatial coverage of our simulations should increase the chances of successful crossings.

Another relevant difference is that the Levison et al. (1973) drifts start at the coast and ours start at distances of tens of kilometers from the coast. By starting further offshore, our drifts have a smaller probability of getting back in the initial days of the experiments.

4.2. Seed drift

Given the lack of data on the effects of seawater on sweet potato seed viability, no definite statements can be made about the feasibility of this crossing as an introduction mechanism. Still, the fastest crossings into Polynesia take 120 days, a period that is longer than the one in which coconuts would remain viable in seawater. This can be taken as an indication that the duration of the crossing in itself would impede viable seeds from reaching the Marquesas. A possibility is that pods drifting not by themselves but attached to ‘‘rafts’’ of floating debris could be protected from the effects of saltwater and still contain viable seeds when arriving at the islands. Transport by rafting of species not adapted to oceanic dispersal is believed to be responsible for the introduction of about 8% of Hawaiian flowering plants (Carlquist, 1981). Rafting is also proposed as the transoceanic dispersal mechanisms responsible for transporting other terrestrial species like frogs, lemurs and monkeys (Houle, 1999; de Queiroz, 2005).

Even if sweet potato seeds could remain viable after the crossing, there is no guarantee that colonization of the plant

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would take place (Sauer, 1993). Still, it is intriguing that hits to the Marquesas and Tuamotu, perceived as likely arrival sites for the sweet potato, show, by far, the highest percentages of occurrence among Polynesian targets.

5. Conclusions

The seed pod drifts have minimum crossing times of 120 days, close to the maximum length of time coconuts remain viable in seawater. This would seem to indicate that drifting seeds would not provide a feasible mechanism for the introduction but reliable conclusions will only be possible when information about the response of the seed pods to the ocean environment becomes available. We plan to conduct experiments to analyze the viability of seed pods after direct exposure to seawater and to natural raft-like conditions.

The relatively high probability of occurrence and relatively short crossing times of vessels drifts from Northern Chile and Peru into the Marquesas, Tuamotu and Society groups are in agreement with the general consensus that this region encompasses the area of original arrival and subsequent dispersal of the sweet potato in Polynesia.

The experiments demonstrate that accidental drift voyages could have been the mechanism responsible for the prehistoric introduction of the sweet potato from the Americas to Polynesia. While present results do not relate to the feasibility of a transfer by purposeful navigation, they do indicate that this type of voyaging is not required in order to explain the introduction of the crop into Polynesia.

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Appendix A

Table A1
Probability of occurrence (%), average time (AvT) and average departure latitude (AvL), for each target size for all vessel crossings

Target	T_{05}			T_1			T_2			T_4			T_6		
	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL
Galapagos N				0.11%	36	1.0	0.61%	38	1.0	0.53%	41	3.2	2.36%	49	4.9
Galapagos S	1.74%	25	−8.0	4.75%	26	−8.7	9.88%	27	−8.5	19.51%	28	−8.5	27.74%	28	−8.8
Easter	1.37%	91	−33.0	4.20%	93	−33.5	7.72%	93	−33.5	14.38%	93	−33.5	16.81%	94	−33.5
Pitcairn	1.77%	125	−31.5	3.53%	130	−30.8	6.54%	131	−30.3	10.82%	131	−30.2	10.38%	131	−30.3
Mangareva	0.95%	129	−30.3	2.28%	131	−30.1	3.77%	133	−30.0	7.01%	135	−30.0	10.02%	137	−29.5
Marquesas N				0.35%	129	21.0	0.23%	131	22.0	0.30%	131	22.0	0.29%	132	21.0
Marquesas S	0.88%	131	−19.5	2.73%	127	−19.9	5.68%	128	−19.8	11.47%	128	−19.8	17.26%	129	−19.3
Tuamotu N							0.69%	133	22.0	1.04%	135	22.0	0.42%	136	22.0
Tuamotu S	0.98%	145	−26.5	2.35%	145	−26.1	4.07%	145	−26.2	7.41%	145	−26.0	9.92%	146	−25.7
Rapa	0.35%	154	−30.0	0.69%	151	−29.5	0.35%	158	−30.2	0.67%	156	−28.5	2.82%	158	−28.4
Australs	0.14%	143	−30.0	0.27%	154	−25.9	0.81%	155	−26.9	1.76%	158	−26.1	3.24%	161	−27.3
Society N													0.69%	160	22.0
Society S	0.57%	149	−25.4	1.14%	152	−25.8	2.43%	154	−26.2	5.00%	155	−25.7	7.31%	157	−25.9
Cooks	0.17%	158	−17.0	0.35%	151	−16.0	0.41%	161	−23.9	0.46%	166	−23.6	0.92%	167	−23.8
Tabuaeran N	3.04%	128	19.7	9.47%	129	19.4	23.47%	130	19.4	39.16%	129	19.9	47.96%	130	19.6
Tabuaeran S	0.56%	149	−15.5	1.11%	153	−16.0	2.08%	153	−15.3	3.25%	152	−15.3	3.92%	153	−15.5
Kiritimati N	0.48%	123	20.0	1.33%	130	18.6	8.25%	127	19.4	22.39%	128	19.2	36.17%	129	19.3
Kiritimati S	0.13%	146	−18.1	0.62%	144	−17.8	1.36%	147	−16.2	3.03%	150	−15.9	4.23%	151	−15.5
Phoenix N	0.29%	123	23.4	0.85%	132	22.8	1.04%	141	22.9	1.88%	142	22.8	2.65%	139	22.6
Phoenix S	0.16%	165	−14.3	0.55%	165	−13.7	1.30%	163	−13.6	2.41%	164	−14.1	4.14%	166	−14.7
Samoa N													0.35%	164	23.0
Samoa S				0.17%	166	−15.0	0.29%	156	−12.6	0.14%	169	−17.9	0.59%	169	−16.2
Tokelau N	0.35%	162	27.0	0.41%	127	25.0	1.69%	145	24.8	2.30%	143	23.9	2.25%	133	24.1
Tokelau S	0.05%	163	−13.0	0.33%	161	−14.1	0.78%	163	−14.0	1.85%	165	−14.7	3.53%	167	−14.4
Tuvalu N	0.14%	154	24.0	0.40%	142	24.0	0.44%	133	24.3	1.16%	140	23.5	1.52%	151	23.2
Tuvalu S	0.29%	161	−11.6	0.40%	164	−10.9	0.18%	165	−10.9	0.40%	168	−11.7	0.44%	170	−12.6
Kiribati N	0.69%	136	24.0	1.07%	140	23.5	2.99%	139	24.4	4.98%	142	23.3	10.27%	145	23.2
Kiribati S				0.04%	158	−14.0	0.24%	167	−15.7	0.43%	168	−16.1	0.76%	171	−15.3
Marshall	1.43%	144	25.3	4.25%	149	24.4	9.12%	148	24.3	11.45%	151	24.8	18.45%	151	24.4
	H_1			H_2											
Hawaii	2.87%	101	26.0	3.42%	102	25.2									

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Table A2
Probability of occurrence (%), average ime (AvT) and average departure latitude (AvL), for each target size for all seed crossings

Target	T_{05}			T_1			T_2			T_4			T_6		
	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL	%	AvT	AvL
Galapagos	1.79%	43	−1.0	7.31%	43	−1.2	17.42%	50	−0.8	28.16%	55	−0.6	29.19%	56	−0.6
Marquesas	0.91%	212	−2.9	1.68%	207	2.9	2.68%	209	−2.8	5.14%	210	−2.8	7.94%	214	−3.1
Tuamotu	0.17%	185	−1.0	0.69%	219	−1.6	1.15%	242	−2.3	1.95%	260	−2.6	3.13%	269	−2.6
Society	0.11%	270	−1.0	0.11%	270	−1.0	0.23%	248	−1.0	0.53%	277	−1.4	0.57%	293	−2.5
Tabuaeran				0.23%	238	2.0	0.21%	220	0.8	0.15%	245	0.0	0.18%	251	−0.3
Kiritimati										0.34%	202	−3.3	0.37%	263	−0.3
Phoenix										0.23%	304	−2.0	0.46%	295	−2.0
Samoa										0.11%	270	−2.0	0.11%	270	−2.0
Tokelau							0.23%	250	−2.0	0.46%	277	−1.8	0.63%	281	−2.3
Tuvalu										0.11%	285	−1.0	0.23%	293	−1.5
	H_1			H_2											
Hawaii	0.11%	370	−3.0	0.11%	360	−3.0									

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