Weapons of Mass Destruction? Rapa Nui *Mata’a* Morphometric Analyses

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Rapa Nui (Easter Island, Chile), a diminutive island located in the remote eastern Pacific, is more than 2000 km from the nearest inhabited island (Figure 1). Polynesians first colonized the island when they sailed from central East Polynesia in voyaging canoes during the 13th century AD (Hunt & Lipo 2006; Wilmshurst et al. 2011). Despite the island's small size, remoteness, and limited natural resources, the archaeological record of Rapa Nui is well-known for its nearly 1000 multi-ton statues known as *moai* that once stood atop massive stone platforms (Hunt & Lipo 2011a). The magnitude of cultural elaboration stands in stark contrast to the island’s desolate environment and low population levels. While earlier researchers (e.g., Heyerdahl & Ferdon 1961a; Heyerdahl 1989) believed the island suffered grave conflict between Polynesians and Native South Americans, subsequent researchers argued that the paradox of the *moai* and the island’s landscape is the consequence of an environmental catastrophe (Bahn & Flenley 1992; Flenley & Bahn 2003). This account has been popularized as the "collapse" scenario (*sensu* Diamond 1995, 2005).

New research challenges this scenario with empirical evidence that demonstrates Rapanui people flourished on the island until AD 1722 when Europeans arrived (Hunt 2007; Hunt & Lipo 2007; Hunt & Lipo 2009a; Hunt & Lipo 2009b; Hunt & Lipo 2011a; Hunt & Lipo 2011b; Lipo & Hunt 2009; Mulrooney et al. 2009; Mulrooney 2012; Rainbird 2002). Contrary to assumptions about large past population sizes, Rapa Nui's settlement patterns show that the inhabitants lived in dispersed and low-density communities (Hunt & Lipo 2011a; Morrison 2012). We also have learned that prehistoric people used lithic mulch to boost the island’s nutrient-poor soil to support sustained cultivation (Bork et al. 2004; Ladefoged et al. 2005; Ladefoged et al. 2010; Ladefoged et al. 2013; Mieth et al. 2006; Stevenson & Haoa 2002; Stevenson et al. 2006). Finally, we now know that the loss of the palm tree forest had little if anything to do with statue transport or a decline in carrying capacity (Hunt & Lipo 2011a; Lipo et al. 2013).

One persistent "collapse" claim is that prehistoric Rapa Nui populations engaged in intense warfare when resources became scarce in late prehistory (Bahn & Flenley 1992; Diamond 1995, 2005; Flenley & Bahn 2003). The island, however, lacks evidence of systematic warfare. There is no evidence, for example, for defensive structures that are common islands on other islands in the Pacific with known traditions of warfare. Instead, claims of prehistoric warfare are largely based on oral traditions recorded in the 20th century (e.g., Routledge 1919). Unfortunately, these accounts have an unknown relation to prehistory and, as Metraux (1940) has argued, likely include recent introductions.

One lingering line of empirical evidence used to infer prehistoric warfare is the abundance of *mata’a* (Diamond 2005; Metraux 1940). *Mata’a* are flaked obsidian tools with narrow stems and wide blades. Overall, their form is similar to stemmed artifacts found on other Polynesian islands such as New Zealand, Pitcairn, Hawai`i, and the Chatham Islands (e.g., Balfour 1917; Metraux 1957: 232; Skinner 1958) as well as on New Britain, Papua New Guinea (e.g., Araho 1997; Specht *et al.* 1988; Torrence *et al.* 2009a; Torrence *et al.* 2009b; Torrence et al. 2013). On Rapa Nui, the vaguely “spear like” shape of *mata’a* combined with oral traditions have led to assumptions that *mata’a* were weapons and thus linked to the presumed “collapse” (e.g., Diamond 2005).

Here we explore whether evidence from the shape of *mata’a* can be used to infer their use as weapons of warfare or some other potential range of functions. Using an image database of 423 complete *mata’a* sampled from four collections, we conduct a quantitative morphometrics analysis: an approach that treats shape as a continuous property of objects rather than nominal categories (Bookstein 1982; Bookstein *et al.* 1985; Bookstein 1997; Cardillo 2010; Kendall 1989). Morphometrics allows one to use multivariate analyses and ordination approaches to test if particular clusters of shapes map to particular locations, environments, or source material. In this way, the approach can lead to the evaluation of hypotheses regarding the potential use environments for these artifacts*.*

# Approach

*Mata’a* have been noted since early European visitors described the island. In 1774 members of Cook's expedition to the island, for example, commented that the islanders “had lances or spears made of thin ill-shaped sticks, and pointed with a sharp triangular piece of black glassy lava” (von Saher 1990: 35). Many of these early visitors assumed *mata’a* were "spears" simply due to their resemblance to European varieties rather than any direct observation of their use. In his voyage to Rapa Nui in 1770, Captain Don Felipe González (Haedo & Roggeveen 1908:99), remarked that "they [Rapanui] possess no arms, and although in some we observed sundry wounds on the body, which we thought to have been inflicted by cutting instruments of iron or steel, we found that they proceeded from stones, which are their only [weapons of] defence [sic] and offence, and as most of these are sharp edged they produce the injury referred to." Thus, it is possible that *mata’a* were used as cutting implements, but not necessarily as lethal weapons.

To avoid making assumptions about function based on what *mata’a* resemble, we can examine the physical evidence of *mata’a* for clues of their prehistoric use. The physical features of *mata’a* shapes and configuration should reflect the range of interactions that occurred between the artifact and their environment. Constraints in shape relative to areas that are free to vary inform us on the parts of object that have performance criteria. Studying shape variability, therefore, provide a means of evaluating hypotheses about use.

*Mata’a* are one of the most numerous shaped artifact classes on Rapa Nui (Figure 2). Overall, they vary in size, but average 6-10 cm in width and length. Technologically, they are formed from unifacial flakes created by hard hammer percussion on obsidian cores quarried from one of the island's four obsidian sources. Most of the shaping of *mata’a* occurs during the creation of a stem through unifacial flaking. Lenticular in cross section, the stem is formed from one of the lateral margins of the original flake, while the blade constitutes the remaining distal and opposite lateral edges. Overall, the shape of the parent flake dominates the resulting blade form.

Notably, *mata’a* shapes are not consistent with the lanceolates usually associated with weapons used to pierce the body, damage internal organs, and incur bleeding. Instead of design optimal for lethal harm, there exist a wide array of shapes ranging from rounded to sub-angular to angular to complex (Mulloy 1961). Early attempts to assign *mata`a* shapes to ethnographic categories using Rapanui words (Routledge 1919) largely failed since clear divisions between shapes and use cannot be identified. Later attempts also focused on identifying types based on characterizations of overall shape (e.g., Mulloy 1961), but these classification did not produce meaningful categories. Mulloy (1961: 151), for example, argued that “no significant clustering or correlations could be extracted.... the material represents a continuous range of variation without objective natural order, and that the only classification possible must involve the subjective selection of ideal types from infinite series of possibilities, and the arbitrary reference of intermediate forms to one or another of these.” Mulloy concluded that manufacturing procedures dictated differences in overall shape of *mata’a* and were best explained by chance. As lethal stabbing implements, such variability would have significant negative consequences in the performance of *mata`a*.

Artifact shape is not necessarily related to function. Artifact forms are the result of processes including technological constraints of the material, performance aspects based on the range of environments of use, as well as simple idiosyncratic variability related to the manufacturer and the process of production. Thus, while shape is not equivalent to function, dimensions of objects may have the potential to affect the relative performance and thus shaped by natural selection (Dunnell 1978). In the case of *mata’a,* it is the blade that interacts with the environment and directly related to its performance in cutting, puncturing, or scraping. Rather than specific shape indicating a narrow range of uses, *mata’a* blade variability can be explained as the contingent results of manufacture rather than specific design decisions (Bollt *et al.* 2006). Studies of use-wear on *mata’a* point to their use in a variety of ways, including scraping and cutting (Church & Rigney 1994; Church & Ellis 1996).

A recent study of *mata’a* shape at the scale of assemblages using deterministic frequency seriation to examine how class frequencies changed over space and through time reveals that *mata’a* forms vary in a remarkably continuous fashion (Lipo *et al.* 2010). The seriation results suggest that at least some of the variability in *mata’a* form, particular shoulder angles and stem shape, was inherited through social learning. The evidence also indicates that variability in the stem portion of *mata’a* is not directly associated performance, but simply a feature of the individual making the object.

In this analysis we address whether blade variability identifies specific functional classes with performance constraints on the shape of the distal portion of the blade. Thus, we focus on variability in the blade portion relative to the stem. We use the point at the center of the stem where it meets the blade to make comparisons. We assume that performance of the functional aspects of the tool will result in shape variability more constrained than those with no performance effects, and are effectively stylistic attributes (Lipo et al. 2012). Constraints related to performance are assumed to sort shape variability in proportion to the benefits/drawbacks. Based on this notion, we hypothesize that:

* If *mata’a* are systematic weapons of warfare, the distal end of the artifact will be constrained in its shape.
* If *mata’a* are systematic weapons of warfare, the distal end of the artifact will show a tendency towards a spear-like shape that is consistent with penetration of enemies or prey. If *mata’a* are not weapons, there will be no such shape restriction of the distal end of the tool.

# Methods

To test these hypotheses, we begin by assuming that the blade portion of *mata’a* shape is a functional element (*sensu* Dunnell 1978), i.e., the portion of the artifact that interacts with the environment. The task of explaining variability in shape consists of identifying selective pressures that affect the performance of shape and to determine whether their magnitude is sufficiently great to affect fitness. The greater the selective pressures on performance, the more constraint we would expect in those aspects of shape. If the effect on function and performance is sufficiently small, then other forces such as technological (i.e., material source, manufacturing steps, etc.) or stylistic (stochastic or neutral) processes may be posited as playing a role in structuring shapes of *mata’a*, as well as when and where they occur in the archaeological record. In aspects of shape not under selection, we would expect to see a greater range of variability. It is possible, however, that not all *mata’a* were used in the same ways. If *mata’a* shape is influenced by more than one function, either contemporaneously or over time, then the selective context will differ and thus the “cause” of *mata’a* shape should vary. In this case we would expect to see modal patterns of *mata’a* shape where outline variants form statistically-distinguishable groups.

To evaluate these ideas, we used morphometrics, a quantitative analysis of form in terms of shape and size, in two or more dimensions (Bookstein 1982; Bookstein *et al.* 1985; Bookstein 1997; Cardillo 2010; Kendall 1989; Rohlf 1990). Morphometric approaches have advantages over traditional studies of shape using global shape descriptors, or lengths and ratios of lengths. First, morphometrics avoids the problem of nominal shape (e.g., "triangular," "square," "round") by transforming the overall shape into independent, quantitative variables. Then, with techniques available for standardizing position, scale, and rotation, morphometrics allows us to explore, compare and test for differences in the shape (form minus size) of artifacts.

With roots in biology, the earliest form of morphometrics focused on identifying the location of specific landmarks (e.g., Thompson 1917). A landmark approach requires defining features examined in terms of how they relate to each other. While *mata’a* share few consistent landmarks, one can analyse "semi-landmarks," a fixed number of regularly positioned points around the outline of an object (Bookstein 1997; Gunz & Mitteroecker 2013). Both approaches to measuring shape make use of the relative positions between all points (Bookstein 1991; 1997). *Mata’a* shapes are clearly in the second case, and we used outline analysis on the basis of semi-landmarks.

# Data

Our dataset consisted of plan-view photographs of artifacts selected randomly from whole specimens available in museum and field collections (Table S1 and S3). We used a collection of 118 *mata’a* from four locations that are currently housed at the P. Sebastian Englert Museum on Rapa Nui. These *mata’a* were collected by Sebastian Englert, William Mulloy, and other researchers and comprise whole *mata’a*. For comparison, we also included eight *mata’a* photographs published by Heyerdahl (Heyedahl & Ferdon 1961a) and 6 *mata’a* that Hunt and Lipo (2008)photographed during pedestrian surveys of land parcels on the south coast of Rapa Nui. Finally, we included photographs of 291 *mata`a* housed Bishop Museum, Honolulu. Mulrooney and colleagues (2014) took photos of these *mata’a* during their study of obsidian sourcing via pXRF. While the Bishop Museum examples do not have provenience information and they may be biased due to their casual collectors seeking specific shapes, we can use this collection to examine shape variability relative to obsidian source (Figure 3). In addition to an overall assessment of shape, this collection of 423 *mata’a* allows us to explore how shape could be potentially be related material properties or by locations. Bootstrap assessment shows that the sample size is sufficient for estimating of basic metrics (Figure S1).

To ensure shapes were directly comparable, we aligned scaled and oriented photos of *mata’a* at the point where the stem midpoint meets the blade. We converted the images to binary format and used TPSDig software (Rohlf 2014) to create outlines of each *mata’a* consisting of 200 sets of X-Y coordinates located equidistantly along the perimeter of each artifact (Figure 4).

Simple metrics of length and width reveal a single distribution of these objects without clear-cut size modes (Figure 5). A more direct means of evaluating shape variability is accomplished by superimposing *mata’a* outlines (Figure 6). To quantitatively analyze these data, we calculated the distance to the perimeter in one-degree intervals for the 360-degree perimeter from a reference point where the center of the stem intersects the blade. This process enables us to examine where shape varies and where it is more constrained (Figure 7). Based on the 95% confidence intervals for the radial distances, *mata’a* shape varies the least at the point where the stem intersects the blade. The systematic shape of the stem likely reflects the manner in which *mata’a* were hafted to a shaft. Stem length, however, varies significantly as does the overall shape and length of the distal blade edge. Importantly, the portions of the *mata’a* shape related to its use and interaction with the environment vary widely.

# Morphometric Analyses: Elliptic Fourier Analysis

Based on elliptical Fourier-based analyses we used *Momocs1* examine the degree to which shape variability forms groups related to specific functions (Bonhomme 2014; Claude 2008; Kuhl & Giardina, 1982; Giadina & Kuhl 1977). Elliptical Fourier approaches treat shape as a periodic function that can be fitted using a sum of simple trigonometric functions. These simple functions are harmonics of one another. Lower harmonics provide approximation for the coarse-scale trends in the original periodic function, while the high-frequency harmonics fit its fine-scale variations (Figure 7, Supplemental Text).

With elliptical Fourier characterizations we can measure *mata’a* shapes to determine if there are clusters that might distinguish sub-groups from each other. Figure 8 presents the position of *mata’a* shapes on a factorial map with shapes reconstructed from the first two principal component axes. Overall, *mata’a* shapes vary continuously in their outlines. There are no subsets of distinctive lanceolate-shaped objects or any other sub-groups. These results suggest that *mata’a* have no single function for which blade shape affects performance and are consistent with use-wear studies that show that *mata’a* edges were used for general cutting and scraping (e.g., Church 1998; Church & Rigney 1994; Church & Ellis 1996; Stevenson & Cardinali 2008: 107).

We can also explore whether there are systematic differences between the locations of *mata’a* or between the obsidian sources used to make them. In our analyses, we used *mata’a* from four sites on Rapa Nui (Table S1 and S3). Figure 9 presents the distribution of sets of *mata’a* from multiple locations across the island (Figure 2). The graph includes the 90% Gaussian confidence ellipses for each of the four sites and the underlying grid represents the morphological space based on the first two principal components. The overlap of the groups indicates that shapes from each of the sites cannot be distinguished. The same conclusion can be drawn from the analysis of the shape variability relative to obsidian source (Figure 10). Overall, there is no evidence that *mata’a* blade shape was constrained due to functional performance, including aspects of location and obsidian source.

# Comparison with stemmed tools from other Pacific Islands

The *mata’a* of Rapa Nui are similar in shape with stone tools found on other islands across the Pacific. On New Britain, for example, Torrence (2009a, 2009b, 2013) has described stemmed obsidian tools that are similar to *mata’a*. Torrence (see also Kononenko 2012) argues that these tools may have been used for a range of activities including tattooing and ritual scarification. An additional but limited comparison can be made with Pitcairn Island, where a few stemmed lithic tools have been found (Heyerdahl & Ferdon 1961b). Our own casual observations include stemmed basalt artifacts known from the Marquesas, Society, and Hawaiian Islands. Stemmed lithics of chert known as locally as *mataa* are also found on the Chatham Islands and on New Zealand (Jones 1981).

As a comparison, we generated outlines of examples of stemmed lithic tools from published images using the same procedure as for Rapa Nui (Table S5). Our elliptic Fourier analyses of shape variability required 13 harmonics to adequately characterize the shape of all of the stemmed artifacts (Figure 11). While the sample sizes of non-Rapa Nui assemblages are small, when we compared to shapes of Rapa Nui *mata’a*, we find that the Pitcairn Island stemmed artifacts have overall shapes that are quite distinct. While we cannot rule out the possibility that the Pitcairn examples are a few extremely long and pointed shapes haphazardly collected from a much wider array of variability, these are more consistent with hafted tools for hunting or weapons. New Zealand *mataa* are similar, but have substantially thicker stems than the Rapa Nui artifacts. Jones (1981) suggests that this might reflect tools that are hafted with the edge perpendicular to the shaft such as an adze. Given their chert composition and relatively steep edge angles, this shape might be well suited for activities such as woodworking.

The New Britain artifacts, on the other hand, show a wide array of features similar to those from Rapa Nui. Based on this comparison, it is conceivable that Rapa Nui *mata’a* functions share those thought to characterize the New Britain tools. Tattooing is known from Rapa Nui through ethno-historic observation (Huish 1839: 77; Métraux 1940; Thomson 1891: 22) and as markings on the prehistoric *moai* (Lee 1992). It would not be surprising that at least some of the *mata’a* objects were used in tattooing and scarification practices.

# ConclusionS

Our investigation of shape variability for Rapa Nui *mata’a* fails to support hypotheses about the potential use of these objects as weapons – or so implied as "weapons of mass destruction" (Keegan 1993). Instead, we gain more support for the use of these artifacts in cultivation and domestic activities as suggested by use-wear analyses (Church & Rigney 1994; Church & Ellis 1996). While the myth of prehistoric Rapa Nui “collapse” and self-destruction remains popular, the evidence to support it is non-existent. Our analysis of *mata`a* blade shape simply does not support their regular intended use as weapons (see also Ingersoll & Ingersoll 2013). There appears to have been no systematic performance requirements that strongly influenced the blade shape. Other than having sharp edges, *mata’a* are no more lethal than any other kind of rock. Indeed, as documented in European accounts of Rapa Nui, rock throwing from high points is the primary way in which native Rapanui fought off intrusion by Europeans and is far more likely to represent potential lethal weapons than *mata’a*. This conclusion does not imply prehistoric Islanders did not experience violence, only that it does not appear be related to systemic warfare where performance as lethal weapons would be paramount.

Our conclusion that *mata’a* had more than one function is not surprising and one must resist the notion that any object is imbibed with inherent function (Dunnell 1978). Instead, we measure function on the empirical variability for assemblages of objects (Dunnell *et al.* 1976). In the case of *mata’a* their wear patterns and frequent occurrence in rock mulch suggest that at least some were employed in cultivation. We also cannot rule out that some *mata’a* may have been used for general domestic and ritual activities such as tattooing and scarification practices. The latter function is consistent with observations of healed scars made by Spanish visitors in AD 1770 (Eyzaguirre *et al.* 1908).

Unfortunately the myth of Rapa Nui “collapse” continues despite any evidence to support it. For Rapa Nui archaeology, tradition has long trumped empirical inquiry as seen in claims about *mata’a* as weapons. And a commitment to the evidence matters. The island's prehistory is often promulgated as an exemplar of the consequences of ignoring human impacts to environment. United Kingdom Prime Minister Margaret Thatcher, for example, famously used Rapa Nui as a warning in a 1989 presentation to the General Assembly of United Nations (e.g., Thatcher 1989). Similarly, *mata’a* have been used as examples of mass effect "weapons" in a study of terrorist tactics (Rasmussen & Hafez 2010). Given the contemporary importance that Rapa Nui has gained in guiding our concerns for our future, we owe it to ourselves to make certain that we fully understand the prehistory of the island and that our understanding is based on well-documented and thoroughly researched evidence.

# FOOTNOTES

*1* For our morphometrics analyses, we used *Momocs* v0.99 (<http://CRAN.R-project.org/package=Momocs>), an R package (R Core Team 2015) developed by Bonhomme (2012; Bonhomme et al. 2014). All of the R code and data for this project is freely available at <https://github.com/clipo/mataaMorphometrics>.

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Figure 1. Pacific Island locations mentioned in the text.

Figure 2. Examples of *mata’a* from Rapa Nui. These *mata’a* are from collections at the P. Sebastian Englert Museum, Rapa Nui.

Figure 3. Locations of *mata’a* collections and obsidian sources on Rapa Nui.

Figure 4. Measurement process used to generate outline coordinates for each *mata’a* in the study. (A) First, we took a scaled digital photograph of the object. We also ensure that images are resized making them equivalent in scale. (B) Second, we isolated the outline of *mata’a* from the background using TPS Dig software (Rohlf 2014). (C) Along the perimeter of the artifact we placed 400 semilandmarks and recorded their x- and y-coordinates. We then use these coordinate data in the morphometric analyses.

Figure 5. Lengths and widths of Rapa Nui *mata’a* in the study. The lengths and widths are normally distributed with only a single mode in each dimension.

Figure 6. Comparison of *mata’a* shapes from Rapa Nui. (A) Superimposed outlines of Rapa Nui *mata’a*. To make comparisons we aligned *mata’a* at the center point of the stem where it meets the blade. (B) Variability in *mata’a* shape shown with mean and 95% confidence intervals. The 95% confidence intervals are shown with exaggerated differences between the values to illustrate areas with greater variance versus those with more constrained shape. Here, the area at the base of the stem where it meets the blade is the most constrained portion of *mata’a* shape, while the stem length and blade are more variable.

Figure 7. Elliptic Fourier analysis is based on the sum of harmonic trigonometric functions, fitting separately x and y coordinates, that together define ellipses in the plane. Five harmonics are here shown at four locations on the original outline of a *mata’a*. As the number of harmonics is increased the reconstruction better approximates the original shape outline.

Figure 8. Results of the Principle Component Analysis (PCA) conducted on the elliptic Fourier descriptions Rapa Nui *mata’a* shapes*.*  This figure shows the first two principal components (PC1 and PC2 are on the x- and y-axis, respectively). Each point represents a *mata’a* described in terms of its shape along these two components. The short lines along each axis show the distribution of the points relative to the individual components. The bar graph at the bottom indicates the amount of shape explained by the first two components relative to the first five components. In the upper left hand corner of the graph are objects that are relatively long and thin while the bottom right hand corner represents objects that are primarily round.

Figure 9. Rapa Nui *mata’a* shapes grouped by site locations arrayed on the first two principal components of the elliptic Fourier shape descriptions. The *mata’a* are shown with the 90% confidence ellipses for the site location groups. MANOVA conducted on the PCA results (Table S2) show that while there is significant overlap between all of the groups, there are some differences in the overall shapes of a couple of sets. The Orongo, Orito and Rano Kau set are significantly different from the group of *mata’a* from unknown locations across the island, a set from the Bishop Museum collection. These differences are potentially related to collection bias. The differences between the shapes of the Orongo and the Rano Kau assemblages are likely explained by the stylistic differences that are demonstrated in seriation analyses of *mata’a* shape classes (Lipo et al. 2010).

Figure 10. Rapa Nui *mata’a* shapes grouped by identified obsidian sources relative to the first two principal components of the elliptic Fourier shape descriptions. The *mata’a* are shown with the 90% confidence ellipses for compositional groups. MANOVA conducted on the PCA results (Table S4) show that while there is significant overlap between the groups, there are some differences between Orito obsidian *mata’a* and those for which we have no obsidian source information. These differences can be attributed to the collection bias inherent the Bishop Museum collection.

Figure 11. Variability in shapes among stemmed lithic objects from Rapa Nui, New Britain, New Zealand, Chatham and Pitcairn Islands. The artifacts are shown grouped by island and arrayed against the first two principal components of the elliptical Fourier descriptions with 90% confidence ellipses. Results of MANOVA for the large assemblages (Table S6) and Wilcoxon rank sum test (Table S7) for the small assemblages show that there are no significant differences between the shapes of the artifacts except for the comparison between the Pitcairn and the Chatham islands, a difference that is likely due to small sample size.

# SUPPLEMENTARY INFORMATION

Our measured outlines are composed of 200 points evenly spaced along the outline of the objects. *Momocs* interpolates between points to locate distances from centroids at even intervals. In addition, since measurements are based on georeferenced coordinates, planimetric measure (such as width or length) can be calculated. Additional image analysis techniques to isolate object outlines point to the strong potential for automation of the measurement process, greatly increasing the ability to characterize large assemblages. With large numbers of measures of radial distances made relative to the *mata’a* centroids, we then calculate a statistical summary for each angle to assess variability in relative dimensions.

In morphometrics, Fourier treats closed outlines as periodic functions. If one starts somewhere on the outline and follows it, one will pass again and again by the same starting point and thus periodic functions can describe this outline. These functions can use a variety of descriptive data for the outline: the distance of any point on the outline to the centroid of the shape, the variation of the tangent angle for any point, or the (x/y) position on the plane (Rohlf & Archie 1984). For an outline shape, a periodic function is obtained and can be decomposed (and thus described) by Fourier series.

Fourier series, however, work on continuous functions. Since in practice shape is measured on a finite number of discrete points on a plane (in our case, x/y coordinates), a discrete equivalent to Fourier series is used in morphometrics. A given number of points called pseudo-landmarks have to be sampled along the outline before computing shape analysis. All Fourier decomposition then result in a harmonic sum of trigonometric functions associated with harmonic coefficients. They are (usually) normalized to remove homothetic, translational or rotational differences between shapes. Two or four coefficients, depending on the approach used, are obtained for each calculated harmonic and can then be considered as quantitative variables. The geometrical information contained in the outlines is thus quantified and can be analyzed with classical multivariate tools.

To conduct Fourier analysis, we must estimate the number of necessary harmonics after examining the spectrum of harmonic Fourier power. The power is proportional to the harmonic amplitude and can be considered as a measure of shape information. As the rank of the harmonic increases, the power decreases and adds less and less information. We can evaluate the minimum number of harmonics required to best approximate the shape. In the case of the *mata’a* and using x/y position for points on the outline as the data set, 12 harmonics provide a good reconstruction of the overall shape (Figures S2 and S3).

Table S1. Rapa Nui *mata’a* included in analyses by site and by repository (N=423).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | *Site* | | | | | |
|  |  | Ahu Tautira | Orito | Orongo | Rano Kau | Parcelas | Unknown |
| *Collection* | Bishop Museum | 0 | 0 | 0 | 0 | 0 | 291 |
| P. Sebastian Englert Museum | 25 | 31 | 29 | 33 | 0 | 0 |
| Heyerdahl & Ferdon 1961a | 0 | 0 | 0 | 0 | 0 | 8 |
| Field Surveys (Hunt & Lipo 2006) | 0 | 0 | 0 | 0 | 6 | 0 |

Table S2. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by site location.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Ahu\_Tautira - Orito | 0.06193215 | 0.2420769 | 22 | 0.957466644 |
| Ahu\_Tautira - Orongo | 0.05560218 | 0.1962527 | 20 | 0.974104678 |
| Ahu\_Tautira - Parcela | 0.2504351 | 0.5011609 | 9 | 0.793418058 |
| Ahu\_Tautira - Rano\_Kau | 0.35941869 | 2.1508146 | 23 | 0.08600363 |
| Ahu\_Tautira - Unknown | 0.06921958 | 1.9211541 | 155 | 0.080653113 |
| Orito - Orongo | 0.20782605 | 0.9619464 | 22 | 0.473111612 |
| Orito - Parcela | 0.35290287 | 0.9998323 | 11 | 0.471607994 |
| Orito - Rano\_Kau | 0.34630248 | 2.2073313 | 25 | 0.076044588 |
| Orito - Unknown | 0.1189607 | 3.5331059 | 157 | 0.002621205 |
| Orongo - Parcela | 0.24543826 | 0.5963331 | 11 | 0.728110499 |
| Orongo - Rano\_Kau | 0.38662672 | 2.6263692 | 25 | 0.040967992 |
| Orongo - Unknown | 0.11393999 | 3.3648169 | 157 | 0.003790983 |
| Parcela - Rano\_Kau | 0.4768608 | 1.9749971 | 13 | 0.142954022 |
| Parcela - Unknown | 0.04653588 | 1.1795064 | 145 | 0.320454247 |
| Rano\_Kau - Unknown | 0.11683632 | 3.4837141 | 158 | 0.00291422 |

Table S3. *Mata’a* included in analyses by obsidian source and collection.

|  |  |  |
| --- | --- | --- |
|  |  | *Collection* |
|  |  | Bishop |
| *Obsidian Source* | Motu Iti | 5 |
| Orito | 279 |
| Rano Kau | 7 |

Table S4. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by obsidian source.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Motu\_Iti - Orito | 0.009766345 | 0.2702371 | 137 | 0.928722366 |
| Motu Iti – Rano Kau I | 0.558319438 | 0.7584478 | 3 | 0.633804963 |
| Motu Iti – Unknown | 0.06662441 | 0.9136648 | 64 | 0.477938757 |
| Orito – Rano Kau I | 0.05378207 | 1.5801239 | 139 | 0.169585655 |
| Orito - Unknown | 0.099580026 | 4.4237147 | 200 | 0.000764068 |
| Rano Kau 1 - Unknown | 0.038861611 | 0.5013679 | 62 | 0.774053529 |

Table S5. Stemmed lithic tools from island locations in the Pacific (N=24).

|  |  |  |
| --- | --- | --- |
| Island | Number | Source |
| Chatham | 8 | Jones 1981 |
| New Britain | 12 | Torrence 2009a, 2009b, 2013 |
| New Zealand | 2 | Jones 1981 |
| Pitcairn | 2 | Heyerdahl & Ferdon 1961b |

Table S6. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by island.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| *Comparison* | *Pillai Statistic* | *Approximate F* | *Degrees of Freedom* | *p-value* |
| Chatham - New\_Britain | 0.60145264 | 0.188639 | 1 | 0.9497193 |
| Chatham - Rapa\_Nui | 0.04067497 | 1.091789 | 206 | 0.3701949 |
| New\_Britain - Rapa\_Nui | 0.05319146 | 1.460673 | 208 | 0.1733617 |

Table S7. Wilcoxon rank sum test of Rapa Nui *mata’a* shapes grouped by island.

|  |  |  |
| --- | --- | --- |
| *Comparison* | *W score* | *p-value* |
| New Zealand - New Britain | 17 | 0.4108 |
| New Zealand - Chatham | 14 | 0.1497 |
| New Zealand - Pitcairn | 4 | 0.3333 |
| New Zealand - Rapa Nui | 725 | 0.0819 |
| Chatham - New Britain | 39 | 0.5116 |
| Chatham - New Zealand | 2 | 0.1497 |
| Chatham - Pitcairn | 16 | 0.04949 |
| Chatham - Rapa Nui | 1606 | 0.08065 |

SUPPLEMENTAL FIGURES

Figure S1. Sample size and *mata'a* parameter estimation. By repeatedly resampling the collection with an increasing number of samples until we reach twice the original sample size while also comparing changes in the 95% confidence intervals of length and width for each set of resampled assemblages, we can assess the degree to which metrics change with increasing samples. The sample size (N=423) shown via the dotted lines) of *mata'a* appears to be sufficient to estimate variability in the basic shapes.

Figure S2. *Mata’a* included in the current analyses. The 5 colors indicate the collection locations on Rapa Nui (Blue=Ahu Tautiri, Green=Orito, Yellow/Green=Orongo, Orange=Rano Kao, Red=Location only known to the level of the island, Yellow=Parcela).

Figure S3. *Mata’a* reconstructed from different numbers of harmonics. Twelve harmonics provide a satisfactory reconstruction.

Figure S4. Cumulated harmonic Fourier power calculated from Rapa Nui *mata’a*. The 12 first harmonics gather nearly 100% of the harmonic power. Maxima, minima and medians are also plotted.

SUPPLEMENTAL TABLES

Table S1: Rapa Nui *mata’a* included in analyses by site and by repository (N=423).

Table S2. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by site location

Table S3: *Mata’a* included in analyses by obsidian source and collection.

Table S4. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by obsidian source.

Table S5. Stemmed lithic tools from island locations in the Pacific (N=24).

Table S6. Results of MANOVA for Rapa Nui *mata’a* shapes grouped by island.

Table S7. Wilcoxon rank sum test of Rapa Nui *mata’a* shapes grouped by island.