EXPLAINING SPATIAL AND TEMPORAL PATTERNS

OF ENERGY INVESTMENT IN THE PREHISTORIC STATUARY

OF RAPA NUI (EASTER ISLAND)

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

ANTHROPOLOGY

DECEMBER 2006

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For my mom and dad

ACKNOWLEDGMENTS

I am indebted to my colleagues, friends, and family that have made this research possible. My high school teacher Nina Goss and undergraduate professor Harvey Wichman are to thank for my interests in writing and research. They were the first instructors that made me realize how important a teacher can be.

My dissertation committee has been a reliable source of support and guidance. I appreciate the time that Nina Etkin and Tom Ramsey have taken with me even though my interests may be outside of their immediate fields of expertise. Tom Ramsey has offered nothing but enthusiasm and encouragement in my work, and Nina Etkin has often helped with difficult career decisions.

Mark Allen first introduced me to the world of academic archaeology and research topics in Oceania. He has always provided sound, honest advice and as my first professor of archaeology eight years ago, he clearly made a lasting first impression. Thegn Ladefoged has taken a genuine interest in my progress and has offered a helpful critical review of this work. Jim Bayman has offered constant encouragement and has helped me to see how my work fits in with other research perspectives in archaeology. I also thank Terry Hunt for teaching a critical approach to research questions that apply to Rapa Nui and the rest of the Pacific. Terry offered me my first chance to travel to Rapa Nui as a teaching assistant on an archaeological field school.

Michael Graves has well-exceeded his duties as committee chairperson. He has helped me to become a better writer, a better field researcher, and he has shown me the importance and rewards of public outreach in archaeology. He has helped me to publish, to find funding, and to find job opportunities. But above all else, Michael stands out for always encouraging me to pursue my own interests.

I am grateful for the generosity and warm welcome that the entire Rapa Nui community has expressed to me. Through their hard work and companionship, Francisco Torres and Verónica Vergara have made my time and research on the island enjoyable and productive. Claudia Peñafiel, Rogelio Paoa, Pelayo Tuki, Pota Paté, and the entire Padre Sebastián Englert Anthropological Museum staff have offered me their friendship and insight for years.

I am very lucky to have the friends I have. They have shown endless support and constantly help me to approach my own research in new ways. Thanks to Jesse Stephen, Ari Levine, Jacce Mikulanec, Dale Simpson Jr., Alex Morrison, Ethan Cochrane, and Derek Robinson for many enlightening conversations. Ethan Levine and Stacey Shepard kindly allowed me to run many hours of computer simulation on their workstation.

My graduate education and several experiences in the field were made possible by generous support from the National Science Foundation Graduate Research Fellowship Program, the Santa Fe Institute Complex Systems Summer School, the National Science Foundation Doctoral Dissertation Improvement Grant, the University of Hawaiʻi Foundation, the University of Hawaiʻi Graduate Student Organization, and the University of Hawaiʻi College of Social Sciences Travel Funds for Professional Improvement.

My parents, Fred and Julia, and my brother, Todd, have shown unconditional support and interest in all of my research and adventures. I cannot imagine being inspired to complete this work without them.

ABSTRACT

This dissertation offers a quantitative analysis of prehistoric Rapa Nui (Easter Island) statuary and an evolutionary interpretation for spatial and temporal patterns of energy investment in statuary. Patterns of energy investment in statuary are considered in the context of cultural as well as environmental variables.

Building on previous quantitative seriation techniques, a new seriation technique (including a new algorithm) is implemented, incorporating radiocarbon/obsidian hydration dates from associated ceremonial sites, to interpret a chronology of construction events for an island-wide survey of 712 prehistoric megalithic statues. The resulting chronology is analyzed statistically and compared to previous chronologies established for other forms of cultural elaboration as well as for settlement sites.

To further test the resulting chronology, and to understand the potential relationship between prehistoric environmental variability and energy investment in statuary, an agent-based computer simulation is presented. A geographic information system (GIS), drawing from previous studies to parameterize Rapa Nui's paleoenvironment, provides initial conditions and basic rules for environmental variables and islander objectives in the simulation.

The simulation offers intriguing results and suggests avenues for future research. Using relatively simple rules and variables, simulation results present justification and explanation for patterns of energy investment hypothesized from chronological seriation of statuary. Evolutionary archaeological and evolutionary ecological interpretations

suggest potential benefits of a heavy expenditure of energy in cultural elaboration (such as statuary) in relation to environmental variability and population dynamics. An extrapolation of these evolutionary explanations presents an intriguing new line of research regarding environmental variability, cultural elaboration, social status differentiation, and an evolutionary model for population sloughing or “cultural autotomy”.

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Chapter 1. Introduction

For thousands of years, prehistoric cultures around the world engaged in the construction of monuments and architecture of astonishing proportions. The cultural elaborations of prehistory fascinate us with their grandeur and sheer aesthetic appeal but also raise anthropological questions. What were the social and environmental conditions that led prehistoric cultures to invest so much time and energy in pyramids, mounds, statues, and tombs? We wonder who the people that built Stonehenge were and what kind of lives they lived. We romanticize the rituals that took place at the Pyramid of the Sun at Teotihuacán nearly two thousand years ago, and the polities and religions that flourished then.

The evolution of culture and the emergence and persistence of cultural elaboration together form an especially intriguing point of investigation in Polynesia, a vast region of the planet that was colonized by humans only relatively recently. Cultures of Polynesia developed in various degrees of isolation and were often forced to prosper within a limited area of inhabitable land and with limited natural resources. Yet, despite the small size and relatively limited resources of the islands of Polynesia, cultural elaboration there often reached impressive scales. Whether these elaborations took the form of temples in the Hawaiian (*heiau*) or Society Islands (*marae*), ceremonial dance grounds of the Marquesas (*tohua*), or the huge stone altars (*ahu*) and statues (*moai*) of Rapa Nui (Easter Island), an immense amount of time and resources were consumed in their creation. Archaeologists, in some cases, encounter great difficulty in explaining how any person or culture can afford to invest so much time and energy in cultural elaboration in the midst of other demands for survival. This dissertation focuses on Rapa Nui and patterns of energy invested in megalithic statuary over space and time.

The aesthetic values, technology, and labor/energy that contributed to the formation of prehistoric monuments in Rapa Nui and elsewhere present a variety of research questions for archaeologists. And archaeologists, in turn, have developed a number of different theoretical perspectives to address research regarding prehistoric monuments. Nearly all of these perspectives have found application and utility at one point or another in Polynesia and Rapa Nui.

Monuments may refer to architecture, statuary, or other structures and are often identified both by their size and by the purpose that the structures were intended to serve. These structures are common to modern and historic cultures around the world, and in some cases, date back to thousands of years before the time of Christ. Although aesthetics, technology, and labor/energy may be inextricably linked in monumental constructions, these topics are pulled apart here for the sake of discussion.

Aesthetics

Some of the earliest deliberate archaeological investigations focused on the architectural or formal details of monuments (Squier and Davis 1848). Archaeologists, as well as ethnologists, quickly realized that architectural or formal similarities among monuments could be identified to determine both temporal and spatial affinities among cultures.

In Hawai‘i (Fornander 1969; Stokes 1991) and elsewhere in eastern Polynesia (Emory 1926, 1933; Green and Green 1968), aesthetic qualities of monumental architecture were used to develop a chronological sequence of population movements within islands. Some studies even proposed aesthetic similarities between monuments to demonstrate a cultural affiliation between islands of eastern Polynesia (e.g., Emory 1939) or between islands of eastern and western Polynesia (e.g., Suggs 1961).

These early interpretations of monuments and monumental architecture were not always accurate in the conclusions that they drew, but provided a foundation for methodology in reconstructing culture historical sequences. More recently, archaeologists have returned to the notion that aesthetic or stylistic qualities of monuments may reflect cultural similarities attributable to either time or space, or both. However, recent efforts in Hawai‘i (Graves and Cachola-Abad 1996), in the Society Islands (Cochrane 2002), in Rapa Nui (Martinsson-Wallin 1994), and in outlier islands (Carson 1998) have been more firmly rooted in evolutionary transmission theory and the archaeological method of seriation.

In Rapa Nui especially, archaeologists continue to identify formal differences among *ahu* (ceremonial platforms) and *moai* (carved images) that are assumed to reflect a gradual change in aesthetic values over time (e.g., Martinsson-Wallin 1994; McCoy 1976; Mulloy and Figueroa 1978; Smith 1962; Van Tilburg 1986; Vargas 1988). With respect to the prehistoric megalithic statuary of Rapa Nui, attempts to describe long-term trends in aesthetics have sometimes been vague and/or subjective (e.g., González et al. 1988). In other archaeological studies on Rapa Nui, aesthetic variability among monuments (or even the mere placement of monuments) has been suggested to reflect spatial segmentation (i.e., territoriality) within the island culture (e.g., Kirch 1984; Shepardson 2005a, 2005b; Stevenson 1984, 1986, 2002; Van Tilburg 1988).

Anthropological inquiries have also documented a similarity across cultures to express differences in social status through residential architectural design. Both in the western Pacific (e.g., Gifford 1929; Tippett 1968) and the eastern Pacific (e.g., Goldman 1970; Tuggle 1979), ethnographers have tended to, “describe the house of the chief as being larger and more ornate than that of the commoner” (Abrams 1989:57).

Despite the temporal and spatial similarities by which monumental aesthetics connect cultures, there are also studies that attempt to express the singularity of each monument’s design. This “phenomenological” approach to the study of archaeological remains tends to emphasize the importance of the manner in which individuals perceive or experience their surrounding natural and constructed environment (Tilley 1994). As each monument is situated in a unique local environment and each culture or individual is prone to a unique cognitive perspective, cross-cultural similarities may be of less importance than an emic interpretation of monumentality. On the other hand, Trigger (1990:119) has argued that, “Some of the more extreme versions of post-processualism appear to be so determined to affirm cultural particularities that they overlook or deny cross-cultural uniformities (Hodder 1986:12).”

Several interpretations of Rapa Nui’s monuments have adopted a phenomenological perspective, associating aesthetic elements of prehistoric iconography with cultural cosmology, evolving ideologies, and sociopolitical organization (e.g., Van Tilburg 1986, 1987, 1988, 1994). The sheer size of monuments ensures that these constructions are in some respects a public display. The post-processual perspective underscores the symbolic value of these displays and the integrative or manipulative effects that such symbols may evoke (e.g., Miller and Tilley 1984; Renfrew 1986).

At the same time, archaeologists have cautioned, as Abrams (1989:53) does, "Some archaeological analyses, however, focus on those symbolic (i.e., psychological and emotional) aspects of artifacts that, although valuable within the holistic and emic conceptualization of culture, are subject to disparate and largely untestable interpretations (e.g., Hodder 1982)". In sum, while approaches to the archaeological interpretation of monumental aesthetics have varied, there appears to be a general consensus that aesthetics are of certain importance and may help us to understand about cultural similarities/differences, but also about social differentiation or power.

Technology

There are those monuments that are so large in scale or so elaborate in design that archaeologists are often urged to consider how they were engineered, transported, and erected given ancient technologies. The megalithic statuary of Rapa Nui, having been transported up to fifteen kilometers in some cases, has drawn speculation on statue transport methods for more than half a century (cf. Einstein 2006:42).

Although investigations regarding statue transport methods rarely stem from larger anthropological questions, there has been no shortage of time or effort devoted to this topic (Adam 1998; Einstein 2006; Lee 1998, 1999; Love 1990; MacIntyre 1999; Mulloy 1970; Pavel 1990; Van Tilburg 1994). Regrettably, without framing technology within the greater prehistoric social context, any information drawn from research on transport methods of statuary or other monuments may be of limited value.

Research has occasionally suggested economic or sociopolitical implications of technologies associated with monumental construction (e.g., Heizer 1966; Peebles and Kus 1977). As Sanders (1965:2) suggests, some archaeologists go so far as to, "define civilizations in terms of excellence of technology, and especially by the presence of monumental architecture." In Rapa Nui, Lipo and Hunt (2005) equate the extent and design of transport routes for megalithic statuary with the political structure or fractioning of the island.

For some archaeologists, the emergence of new forms of monuments connotes a technological specialization that reflects on sociopolitical complexity. Specialization in monumental construction, much like specialization in smaller crafts, may indicate a new form of employment in a growing or changing economy (e.g., Abrams 1989:61; Heizer 1966:828). Elsewhere, control over such emergent technology is suggested to impart sociopolitical power upon individuals (e.g., Peregrine 1991). In western Polynesia, Burley (1998:324) claims that, "The elaboration of the stone construction industry in Tonga significantly marks [a correlate of socio-political complexity], and it provides a rare opportunity to examine the interrelationships of professional crafts and emergent political structures."

And finally, for certain cultures, the monuments themselves (rather than the engineering, transport, or erection) marked a technological advance. Several decades ago, archaeologists began to demonstrate monument designs or alignments that coincided with celestial phenomena (e.g., Hawkins 1965; Renfrew 1973). Recently, Kirch (2004) has demonstrated archaeoastronomical correlations for stone-and-earth platforms in Mangareva. And on Rapa Nui, Liller (1993a) asserts that certain monuments may have acted as "ancient solar observatories". Thus, the emergence or elaboration of monuments may indicate advances in technology as well as the collective knowledge of a culture.

Labor/Energy

Despite lasting interests in aesthetics and technology, archaeological interpretations of monuments have shown an even greater focus on the vast amount of human labor or energy that was invested in these constructions. In a fundamental way, as Price (1982:720) asserts, "Whatever else a material object may represent, it *is* directly the energy expended on it."

Between the 1940's and 1960's, energy was often placed at the theoretical helm of anthropological interpretations. In a thermodynamic approach, White (2002:402) concluded that, "culture advances as the amount of energy harnessed per capita per year increases, or as the efficiency or economy of the means of controlling energy is increased, or both." Technology, for White and his contemporaries, was the means by which a culture became capable of harnessing energy more efficiently. Thus, while the previous section of this introduction referred to that technology *directly* associated with monuments, White's discussion of technology is linked to monuments only *indirectly*.

Monumental construction, according to White's perspective, is evidence of a certain level of energetic efficiency that researchers associated with cultural stages within an index of unilineal evolution (e.g., Childe 1950, Fried 1967; Service 1962). Regional studies in the Americas (e.g., Erasmus 1965; Heizer 1960; Sanders and Price 1968) and elsewhere (e.g., Adams 1967) began to frame the "scale of architecture as an index of labor access and control and thus of cultural development" (Abrams 1989:50).

Over time, anthropologists became increasingly uncomfortable with the simplistic correlations between architecture and cultural types as well as the unilineal approach to cultural evolution. Studies became more concerned with the particular environmental conditions with which individual cultures were forced to cope (Steward 1955). Structures or architecture resulting from massive amounts of cooperative labor (e.g., fortresses, irrigation networks, etc.), were often explained as the result of a population either choosing or being forced into a sociopolitical organization that was a direct result of ecological pressures (e.g., Carneiro 1970; Wittfogel 1957). The ecological approaches to complex societies saw only limited success. The work of Flannery (1968, 1972) and Peebles and Kus (1977), on the other hand, stressed the importance of both ecological and humanistic variables. In their systemic analyses, labor investment in monumental architecture may have been necessary to finance or regulate one or more of the interrelated institutions that compose a functioning culture.

Empirical examples, especially resulting from Earle's (1978, 1987) work in Kaua'i, also seemed to contradict the idea that sociopolitical organization was merely a response to subsistence concerns. Rather, archaeologists began to adopt a political economy perspective (Brumfiel and Earle 1987). As Earle (2002:1) explains, "The political economy is the material flows of goods and labor through a society channeled to create wealth and to finance institutions of rule." From this perspective, Earle (2002:335) continues, “the labor invested in monumental construction helps to determine the extent of central control over people.”

The political economy perspective has been widely adopted in Polynesian archaeology. Graves and Sweeney (1993:113) suggest that for archaeological interpretations of monuments in Rapa Nui and Hawaiʻi, “these features are generally inferred to reflect the management of sizeable labor forces and the control of resources by elite groups (Kirch 1990; Kolb 1992; Mulloy and Figueroa 1978; Stevenson 1986).” Thus, rather than being viewed as the outcome of environmental pressures, investment of energy in monuments and monumental architecture may also be viewed as a mechanism by which elites either establish or maintain positions of power. The political economy view echoes, to some extent, the earlier works of Veblen (1899) and Zipf (1949), who suggested that conspicuous consumption of resources was designed to enhance social prestige or power.

Only recently have archaeologists begun to consider the impacts of energy investment in monuments in terms of biological, rather than sociopolitical, success (Boone 2000; Dunnell 1989, 1999; Graves and Ladefoged 1995; Graves and Sweeney 1993; Hunt and Lipo 2001; Ladefoged 1993; Madsen et al. 1999; Neiman 1997). In these studies, energy investment in monuments is proposed to be a short-term tradeoff for long-term gains in fitness, often in a variable or unpredictable environment. These studies tend to distinguish a *scientific* evolutionary approach from *cultural* evolutionary approaches (Graves and Ladefoged 1995).

Clearly, there have been many different perspectives in the archaeological or anthropological interpretation of monuments and monumental architecture. This dissertation combines one of the oldest culture historical methods (seriation) with computerized geographic information system (GIS) models and agent-based computer simulations to develop a scientific evolutionary explanation for spatial and temporal patterns of energy investment in the megalithic statuary of Rapa Nui. The dissertation builds on a recently-gathered database of more than 700 megalithic statues, and considers trends of energy investment in statuary both over time and space in light of key paleoenvironmental variables. And although the concluding explanations for patterns of energy investments in monumental statuary are based largely on evolutionary archaeological and evolutionary ecological work, this dissertation also demonstrates a unique connection between sociopolitical complexity (or hierarchization) and biological success. The "cultural autotomy" model (see Chapter 7) presents a bio-cultural phenomenon by which a rigid distinction between levels within a social hierarchy may present optimal means for sloughing the minimum subpopulation necessary to endure climatic or other pressures imposed upon a population.

Perspectives on Rapa Nui Prehistory

Concerning archaeological investigations of the *moai* (statuary) of Rapa Nui over the last century, a clear progression of thought reflects advances in North American archaeological theory. The earliest inquiries focused on description rather than explanation and can aptly be categorized as culture historical. Thomson (1891), at the close of the 19th century, Routledge (1919) early in the 20th century, and Englert (n.d.) in more than thirty years following the work of Routledge, conducted island-wide surveys of statues. Their work formed the foundation upon which all later studies of the statues have been based.

Cultural evolutionary studies followed. Building on data accumulated in previous decades, researchers synthesized massive amounts of ethnographic material to create a comprehensive and coherent picture of systematic evolutionary progress for Rapa Nui and Polynesia in general (e.g., Goldman 1955; Sahlins 1958). These studies often related evolutionary progress to potential in environmental productivity. Thus, complexity and elaboration on large, tropical islands like Hawai‘i and Tonga were readily explained, while the “esoteric efflorescence” of the small and relatively impoverished Rapa Nui remained anomalous to traditional explanations (Sahlins 1955).

Subsequent research has diversified, providing several different archaeological explanations of monumental architecture. The stylized and iconographic nature of monumental architecture and imagery has provided a basis for interpretations of proximate causes of labor investment in statuary, including traditional value systems, religious beliefs, and a daily lifestyle (e.g., Bahn 1993a; Raphael 1988; Van Tilburg 1986, 1994).

While the hallmark of Rapa Nui prehistoric culture in the popular imagination has been the enormous stone *ahu* and *moai*, nearly a century’s worth of anthropological work on the island has provided a more extensive picture of the island’s prehistory. The triangular island (at 27°09’30”S and 109°26’14”W), formed by three shield volcanoes (Poike, Rano Kau, and Terevaka), at present covers little more than 163 km^2 and is

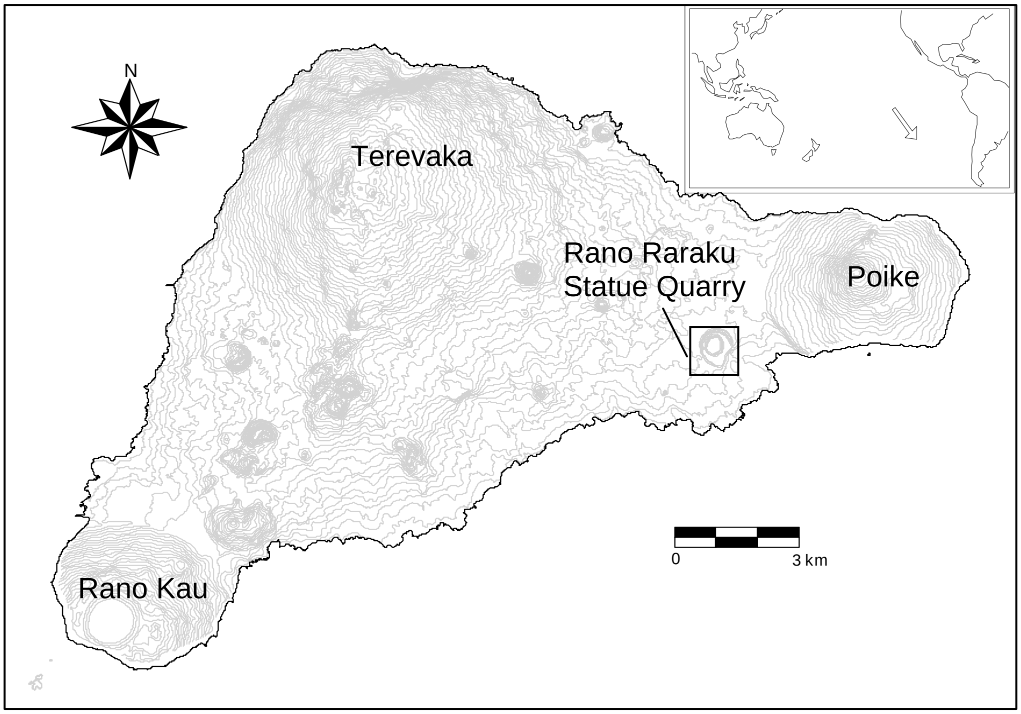


Figure 1.1. Rapa Nui (Easter Island) and Pacific context.

located more than 2000 kilometers from any other inhabited land (Figure 1.1). Despite its relative isolation, Polynesian voyagers discovered and colonized the island sometime between AD 690 (Bahn 1993a) and 1200 (Lipo and Hunt 2006). In the centuries afterwards, until European contact in 1722, a unique and elaborate Polynesian culture flourished on Rapa Nui.

Routledge (1919) suggested a population that reached between 37,000 and 52,500 at its peak, yet other scholars have estimated a peak more conservatively between 6,000 and 10,000 (e.g., Bahn 1993b; Kirch 1984; McCoy 1976, 1979; Owsley et al. 1994). Researchers have mapped and documented the types of stone enclosures used for shelter, agriculture, and animal husbandry (e.g., Cristino and Vargas 1980; Cristino et al.

1981; McCoy 1976; Vargas 1989; Vargas et al. 1990). And we now know of the terrestrial and marine resources regularly exploited by the prehistoric culture (e.g., Butler and Flenley 2001; Flenley 1993; Flenley et al. 1991; Hunter-Anderson 1998; Martinsson-Wallin and Crockford 2002; McCall 1979; Orliac and Orliac 1998; Stevenson et al. 2002).

Typically, archaeological investigations on Rapa Nui for the last five decades have led researchers to devise three phases for Rapa Nui's prehistory, largely based upon those formulated by the first stratigraphic investigations on the island by the Norwegian Archaeological Expedition (Heyerdahl 1961a, 1961b). In some cases, the sequence has been subsequently expanded and/or revised (e.g., Ayres 1975; Hunt and Lipo 2006; Kirch 1984; Lee 1986; Stevenson 1997; Van Tilburg 1986). From the time of colonization until roughly AD 1100 was the *ahu moroki* phase—a time when settlers and their transported domesticates such as yams, taro, chickens, rats, etc. were adapting to a new homeland (Métraux 1940; Mieth et al 2002; Wozniak 2001). Additionally, in this first phase ceremonial centers including *ahu* were first constructed (Ayres 1971; Kirch 1984; Martinsson-Wallin 1994; Mulloy and Figueroa 1978; Skjølsvold 1994). Following the *ahu moroki* phase, and lasting until sometime between 1500 and 1680 was the *ahu moai* phase. In these years, the island is thought to have experienced rapid population growth, the proliferation of giant stone statuary as well as other new architectural features, and developments in sociopolitical complexity. Finally, the *huri moai* phase began after the *ahu moai* phase and terminated around 1868 with missionary work on the island (Smith 1962). During this final phase, the statues that once stood atop *ahu* were pulled to the ground, *ahu* were converted to shelters or burial sites, and obsidian artifacts were manufactured in abundance. Generally, the *huri moai* phase is suggested to have been characterized by endemic warfare, a shift in religious ideology, and pervasive cultural decline (Kirch 1984).

Collapse?

In the most simplistic presentations, the popular three-phase prehistoric sequence is interpreted as a culture's colonization and growth, rise to unsustainable peak, and subsequent catastrophic collapse. Within this culture history, the *moai* industry is often portrayed as part of an extravagant lifestyle that was doomed from the start and, as a cause of environmental degradation, led to near-extinction for the prehistoric island culture (e.g., Bahn 1993a; Bahn and Flenley 1992; Diamond 1995, 2005; Flenley and Bahn 2003; Kirch 1984, 2000; Kirch and Green 1987; McCoy 1979; Wright 2004). As Kirch (1984:264) summarizes, prehistoric Rapa Nui culture is one that is thought to have, "temporarily but brilliantly surpassed its limits and crashed devastatingly."

Some of the most recent archaeological efforts, however, have begun to question the soundness of the simplistic and speculative rise-and-fall account of Rapa Nui prehistory (e.g., Rainbird 2002; Young 2006). Furthermore, archaeological investigations stemming from a scientific evolutionary perspective have contested that, "the construction of stone monuments did not cause the destruction of the island's population and culture, but may well have fostered their persistence" (Hunt and Lipo 2001:108).

Differing interpretations of the costs or benefits of intense cultural elaboration and large-scale investment of energy in monumental statuary have culminated in two opposing accounts of cultural evolution in prehistoric Rapa Nui. There is the possibility that the resources required in maintaining a tradition of cultural elaboration and monumentality eventually overtaxed the local environment, and as a result, cultural practices effectively triggered a severe ecological and social collapse late in prehistory. However, there is also the possibility that the collapse was largely unrelated to Polynesian cultural traditions. On one hand, the tiny subtropical island may have been doomed by its relative isolation or limited resources from the start, and construction of megalithic monuments may have played little role at all in the onset of cultural and ecological disaster. On the other hand, repeated population bottlenecks prior to European contact may have been a phenomenon from which the island and its population regularly recovered. Furthermore, insistence on a self-induced catastrophic collapse may simply be, as Van Tilburg (1994:164) writes, "…a projection of Western values which emphasizes the self-destruction of Rapa Nui culture over the actual, near-annihilation of it by contact with the West."

The differing accounts of Rapa Nui prehistory are cause for concern and merit critical attention from archaeologists. If there truly was a self-induced catastrophic collapse late in Rapa Nui prehistory, the island may serve as an alarming parable of our own potential worldwide fate from which we may learn the values of resource management.

If some form of collapse on the island was inevitable, or if Europeans rather than Polynesians were responsible for the so-called collapse, then Rapa Nui may be an example of a prehistoric society terribly misinterpreted by recent syntheses. Archaeological interpretations and conclusions regarding prehistoric islanders' incompetence in resource management may not only be flawed but also damaging to the identity and pride of direct descendants that continue to live on Rapa Nui, in Chile, and scattered elsewhere around the world today.

Regardless of whether Polynesians caused the collapse, Europeans caused the collapse, or if such a devastating collapse even occurred prior to European contact, the focus on such an event has greatly oversimplified common perception of prehistoric cultural evolution on Rapa Nui. The ever-present discussion of a collapse reduces several centuries of complex ecological and cultural dynamics to a brief sequence of events in late prehistory.

As Rainbird (2002:439) suggests, "This story of self-induced ecodisaster and consequent self-destruction of a Polynesian island society continues to provide the easy and uncomplicated shorthand for explaining the so-called cultural devolution of Rapa Nui society."

Selected Topics in Rapa Nui Prehistory

The catastrophic collapse that accents the rise-and-fall interpretation of Rapa Nui prehistory distorts and confounds several anthropological topics that might otherwise be investigated and interpreted in more detail. Central to the notion of cultural collapse are the themes of conflict, warfare, and territoriality.

Conflict and warfare are prevalent in Rapa Nui oral traditions regarding late prehistory (e.g., McCoy 1979; Métraux 1940; Routledge 1919), but oral traditions recounting alleged massive violent encounters are not always corroborated by archaeological investigation (Love 1989). Although warfare certainly existed in some capacity in Rapa Nui prehistory, the dynamics of interpersonal or intergroup conflict on the island are not addressed in explicit detail in this dissertation. However, the dissertation does rely on an explicit division between sociopolitical groups on the island as the foundation for spatial analyses. And in some ways, territorial boundaries may serve as a proxy for causes and/or effects of conflict. Warfare on Rapa Nui may have led, in separate instances, to integration of social groups, but also to obvious separations between groups (McCoy 1979). Previous archaeological research in the Pacific may help to demonstrate potential links between warfare and sociopolitical boundaries, both through the beneficial integrative consequences of warfare (e.g., Allen 1994, 2003; Allen and Arkush 2006; Feil 1987; Ladefoged 1993, 1995; Liston and Tuggle 2006; Sillitoe 1978; Webster 1975) and the political fragmentation that may be related to competition or conflict (e.g., Allen 2003; Allen and Arkush 2006; Earle 1997; Hunt 1988; Kirch and Green 1987).

In studies of Rapa Nui prehistory, territoriality has received extensive interest, historically from ethnologists and more recently from archaeologists. Work on territoriality and a potential link between monuments or monumental architecture and sociopolitical boundaries have demonstrated great potential for a more comprehensive understanding of the topic (Rounds-Beardsley 1990; Shepardson 2005a, 2005b, 2006a; Stevenson 1986, 2002). Several different territorial schemes, of varying levels of complexity, have been identified for the island. Ultimately, however, the bulk of analysis in this dissertation refers to a simple two-part division of the island first described by Katherine Routledge (1919): north and south.

The notion of collapse also includes the topics of population dynamics, environmental productivity, and cultural elaboration. These anthropological topics form the focus of this dissertation. Cultural collapse is composed, at least in part, by acute changes in population size or demographic variables. A severe bottleneck was recorded for Rapa Nui in 1877 when the population reached a low of 111 individuals (Fischer 2005; Owsley et al. 1994). This was, however, well after the first Europeans arrived in 1722 aboard the three Dutch vessels commanded by Jacob Roggeveen. The population bottleneck late in the 19th century was a product of "blackbirding" or kidnapping of Rapa Nui islanders for work as indentured servants in Peru and the introduction of smallpox, among other diseases, to the island.

Determining whether there was a severe collapse or population bottleneck prior to European contact is more difficult. Estimating prehistoric population size from archaeological evidence can be imprecise and problematic (Kirch 1984). Yet, since Suggs' (1960, 1961) work in the Marquesas, anthropologists have been well aware of the importance of reconstructing demographic variables and continually attempt to do so. For Rapa Nui, peak population estimates have varied wildly. In some cases, these estimates may have been little more than speculation. More diligent efforts at estimating population size and growth have appealed to settlement pattern studies (McCoy 1976) along with extensive collections of obsidian hydration dates for habitation sites (Stevenson 1986, 1997). Obsidian hydration dates act as a proxy for population dynamics in this dissertation to help assess and interpret analytical results regarding the chronology of statue construction derived in this dissertation.

Discussions or interpretations of Rapa Nui prehistory have frequently hinged on an ecological collapse as well as a cultural one, and in many cases the two may be closely related. For several decades, Rapa Nui has drawn attention for hosting a natural environment that has apparently undergone major transformations—from the indigenous flora and fauna, which were later exploited (in some cases to extinction) and appended by Polynesia introductions, to the plants and animals that were imported by Europeans and that now dominate. People, along with the species that they have introduced, have drastically altered the Rapa Nui environment. Furthermore, through technological advances (both prehistoric and modern) the manner and rate at which islanders exploit or alter the landscape have also changed. An "ecological collapse" is a subjective and potentially misleading qualitative statement about the evolving condition of the Rapa Nui environment. However, careful research is beginning to express environmental conditions and changes in more objective, quantitative terms for topics such as deforestation (Butler and Flenley 2001; Flenley 1993; Flenley et al 1991; Hunter-Anderson 1998; Mieth et al. 2002; Mieth et al. 2003; Orliac 2000), water availability and management (Gossen and Stevenson n.d.; Martinsson-Wallin 1994), and soil fertility (Ladefoged et al. 2005). By doing so, paleoenvironmental studies help to determine the relative environmental productivity for different regions of the island at different times. In the Pacific, recent studies have attempted to demonstrate potential links between environmental productivity or variability and population growth (e.g., Field 2003; Hunt and Lipo 2001), group conflict (e.g., Allen 1996, Arkush and Allen 2006; Ladefoged 1993, 1995), and cultural elaboration (e.g., Graves and Cachola-Abad n.d.; Graves and Sweeney 1993; Graves and Ladefoged 1995). This dissertation reviews research on a number of key environmental variables and considers how spatial and temporal variability in the availability of these resources may have interacted with a growing population and a predilection for cultural elaboration.

Cultural elaboration is often suggested as a critical link between the purported cultural and ecological collapse of Rapa Nui prehistory. Specifically, it is the abundance of prehistoric megalithic constructions on Rapa Nui that are thought to be evidence of, and responsible for, unsustainable consumption of natural resources. Cultural evolutionary studies have tended to relate statue construction (as a particularly visible form of cultural elaboration) not only with prehistoric cultural complexity but also with high productivity levels in the island environment (e.g., Bahn and Flenley 1992; Diamond 1995; Kirch 1984). Termination of statue construction by the 18th century, according to the cultural evolutionary perspective, indicates a decline in cultural complexity and receding productivity in the natural environment. In concert, reduced cultural complexity and environmental productivity form the alluring collapse explanation for Rapa Nui prehistory.

There may be little argument that construction of statues and megalithic architecture resulted in the consumption of vast amounts of natural resources. However, evolutionary archaeological and evolutionary ecological studies have identified both short- and long-term impacts of investment of resources in statuary and cultural elaboration that may not always be to the detriment of a culture's survival (Boone 2000; Dunnell 1989, 1999; Graves and Ladefoged 1995; Graves and Sweeney 1993; Hunt and Lipo 2001; Ladefoged 1993; Madsen et al. 1999; Neiman 1997). In the short-term, investment or pooling of resources for the construction of monuments can help to form beneficial relations that facilitate trade, ameliorate intergroup aggression, and enhance reproduction. In the long-term, construction of monuments can act as an investment to hedge risks associated with subsistence strategies in variable or unpredictable environments.

This dissertation analyzes investment of energy in statuary for an extended period of Rapa Nui prehistory. Results are considered in light of our understanding of paleoenvironmental variables and population dynamics to test the theoretical sufficiency of cultural evolutionary, evolutionary archaeological, and evolutionary ecological explanations for the persistence and variability of monumental statuary throughout Rapa Nui prehistory. The concluding analysis and discussion emphasize the potential in the methods applied throughout the dissertation as well as the potential in building upon explanations derived from a scientific evolutionary perspective.

The results and conclusions drawn from this dissertation are not necessarily correct, but appear to be congruent with current research perspectives on population dynamics, environmental productivity, and cultural elaboration for Rapa Nui prehistory. Additional research is required for a clear understanding of almost all aspects of cultural and ecological evolution on Rapa Nui, and results from the work described herein may help to guide future research initiatives. Furthermore, methods applied throughout the dissertation are, in some respects, exploratory. Conclusions drawn from the analyses may continue to be refined with future applications of these methods to research questions on Rapa Nui and elsewhere.

Methods

In order to begin to measure variability in energy investment in prehistoric statuary, both over time and space, a chronology of statue construction events is first required. To determine the timing of individual statue-manufacturing events, measurements of formal features of 712 statues, from a field survey conducted as part of the research for this dissertation (Figure 1.2), are subjected to a seriation analysis. Seriation is a mathematical technique that archaeologists have relied upon for nearly a century to analyze the stylistic variation in artifacts over time (Petrie 1920). Seriation requires a large amount of descriptive data for artifacts, but has the potential to produce detailed relative orderings of like artifacts based on their formal similarities. These relative orderings can be further constrained or bounded by radiocarbon dates for the construction of *ahu* (ceremonial platforms) that are assumed to predate specific statues.

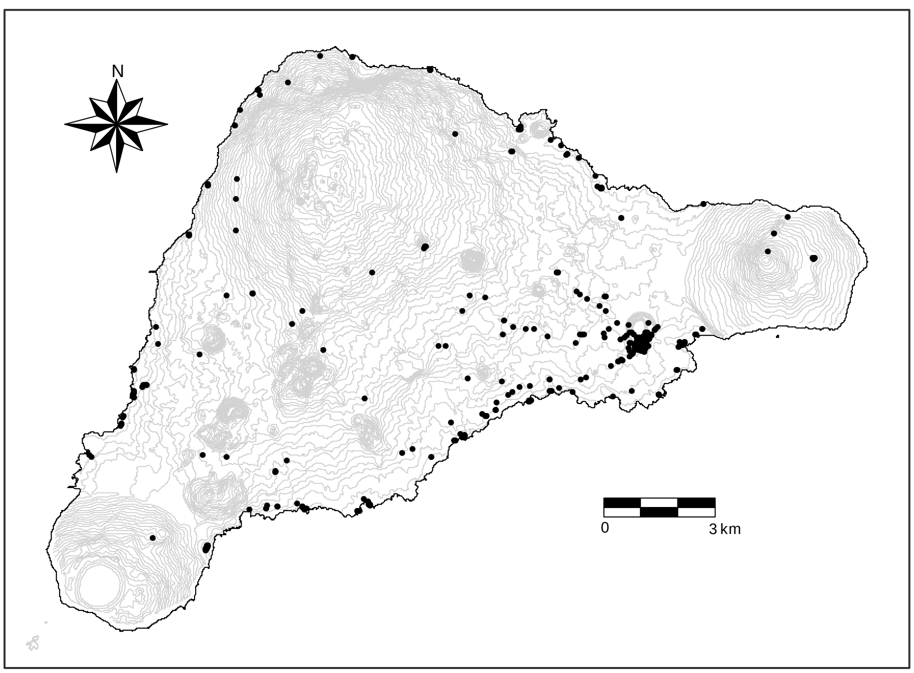


Figure 1.2. Rapa Nui and distribution of 712 statues. Some dots may represent multiple statues.

The chronological results of any seriation analysis deserve a critical and conservative review. Any theoretical mathematical representation of the real world will necessarily misrepresent empirical processes or events to some extent. Only time and extensive statistical testing of the proposed seriation technique may help to determine the confidence we can associate with a chronological ordering of the statues. Therefore, seriation results are proposed only as a hypothetical chronology of statue construction which is subsequently tested through computer simulation of cultural and environmental processes.

Computer simulation is an archaeological technique that has not yet been applied extensively to Rapa Nui. However, computer simulation has proven to be a valuable tool in formulating predictive models elsewhere in archaeology (e.g., Dean et al. 1999; Lake 1999; Lansing 1999; Rauch 2002), and the potential for the applicability of simulation to Rapa Nui prehistory has been demonstrated in a preliminary manner (Shepardson 2006b).

Specific aspects of Rapa Nui's paleoenvironment (potable water resources, forest resources, rainfall, marine resources, and agricultural resources) are incorporated into a GIS database to create baseline conditions for the simulation of Rapa Nui's prehistoric environment. The environmental variables directly influence virtual islanders that populate the simulated Rapa Nui environment. Comparison of temporal-spatial variability in population and resources to the hypothesized chronology of statue construction events allows for a discussion of potential evolutionary relationships between population dynamics, environmental productivity, and cultural elaboration.

Dissertation Summary

Chapter 2 discusses a new analytical seriation technique, optimal path seriation (Shepardson and Shepardson 2004a), developed as part of the research for this dissertation for the specific goal of interpreting a chronology of statue construction for prehistoric Rapa Nui. This is the first object-scale analysis of a large group of statues to be published for Easter Island. Based on previous mathematical approaches to archaeological seriation, optimal path seriation (OPS) orders statuary according to their similarities or differences across a suite of formal variables and assigns specific construction dates to individual statues according to degree of formal similarity and published dates from associated architectural remains. In some respects, OPS remains as an exploratory analytical technique. However, empirical testing as well as a demonstrated mathematical relationship with traditional seriation techniques offers some indication of the analytical potential of OPS. Appendix A offers an explicit axiomatic derivation of the OPS algorithm as a supplement to Chapter 2.

Chapter 3 implements the optimal path seriation algorithm through *OptiPath* software (Shepardson and Shepardson 2004b) for a detailed analysis of formal variability amongst prehistoric Rapa Nui statuary. The analysis considers different combinations of formal variables and different subsets of statuary in distinct seriations. Each seriation produces slightly (or sometimes significantly) different orderings for different subsets of statuary. The degree of similarity for statue dates across a group of seriations is used as an indication of the accuracy or plausibility of seriation results. Ultimately, dates for the construction of individual statues are averaged over a group of seriation results and a single averaged ordering is selected for further analysis in subsequent chapters.

Chapter 4 presents temporal and spatial estimates for energy investment in prehistoric statuary based on the statue chronology derived in Chapter 3. Energy estimates are calculated as a sum of energy costs associated with the carving, transport, and erection of individual statues. Estimates for energy investment in statuary demonstrate intriguing parallels to prior studies of temporal-spatial patterns in construction of alternative forms of prehistoric monuments. Chapter 4 may reiterate the significance of a previously recognized geographic distinction between the northern and southern regions of Rapa Nui and establishes the north/south division as a foundation for analyses throughout later chapters.

Chapter 5 reviews literature pertinent to the development of a computer simulation (*RapaSim*) of prehistoric ecological conditions for Rapa Nui. Five critical elements of the Rapa Nui environment are identified: potable water resources, timber, rainfall, marine resources, and agriculture. Although much research remains to be completed to enhance our understanding of these five ecological elements, existing data and publications help to parameterize and offer reasonable initial conditions for the computer simulation. Appendix B presents a description of the simulation interface and user controls for *RapaSim*.

Chapter 6 begins by exploring some of the large-scale effects of environmental variables within the computer simulation, drawing special attention to the potential importance of the distribution of potable water sources on the island. The remainder of the chapter describes specific simulation results that correspond to patterns of energy investment in statuary calculated from seriation results from Chapters 3 and 4. In this context, computer simulation serves as a "weak" test of the statue chronology hypothesized by the optimal path seriation analysis. That is, rather than attempting to falsify the hypothesized chronology, computer simulation helps to demonstrate simple and reasonable environmental and social conditions that may account for hypothesized patterns of energy investment in prehistoric statuary. Episodes during which populations are sustained at a level near the regional carrying capacity appear to coincide with, or may precede slightly, those time periods during which energy investment in statuary was exceptionally high. Interestingly, simulation conditions that produce these results do not presume catastrophic downswings in carrying capacity.

Chapter 7 exposes several of the limitations in the scope and methodology of the research presented throughout the chapters. Some of these limitations highlight potential avenues for future research while others may be ingrained in current archaeological methods or theory. And finally, Chapter 7 summarizes the results of seriation and simulation analyses in light of current explanations for cultural evolution and energy investment in statuary for prehistoric Rapa Nui. Conclusions drawn from the analysis help to demonstrate strengths and weaknesses of existing explanations. Furthermore, a discussion of evolutionary interpretations of both biological and social conditions relating to cultural elaboration and monumentality yield a novel interpretation ("cultural autotomy") of potential evolutionarily beneficial impacts of large-scale energy investment.

Financing ostentatious monuments may be a manner in which individual or lineage status was established or reinforced. The evolutionary benefits of high status resulting from monumental constructions, perhaps most importantly in maintaining access to critical resources even in times of stress, have already been explored (e.g., Boone 2000; Graves and Ladefoged 1995; Graves and Sweeney 1993; Dunnell 1989, 1999; Madsen et al. 1999). Chapter 7 revisits these benefits and acknowledges their role in preventing catastrophic population collapses. However, Chapter 7 also discusses a model of optimal population sloughing (cultural autotomy). Social status, specifically the establishment of a low-status subpopulation (one with low priority in access to resources and consequently one that is particularly vulnerable to stress) may not only prevent catastrophic population collapse but also minimize overall population decreases, during times of environmental or climatic stress. In the long run, minimizing failure may equate to maximizing population success. The concluding discussion in Chapter 7 builds upon existing evolutionary explanations to introduce a more holistic interpretation of the evolutionary consequences of energy investment in monuments or cultural elaboration.

The "cultural autotomy" model is an original contribution offered by this dissertation to account for patterns resulting from seriation and simulation analysis of Rapa Nui prehistory. As the cultural autotomy concept is still in its formative phase, specific empirical tests for the model have yet to be developed. Thus, explicit archaeological evidence for cultural autotomy, or efficient and rapid sloughing of populations, on Rapa Nui is not presented as part of this research. However, the proposition of cultural autotomy, as a viable evolutionary strategy (designed purposefully or otherwise), demonstrates the value and potential of applying innovative research methods to a case study of prehistoric Rapa Nui.

CHAPTER 2. OPTIMAL PATH SERIATION

The prehistoric megalithic remains of Rapa Nui are a major component of the island's archaeological record. The *moai*, or statues, are just one example of the megalithic remains but form the focus of this study. *Ahu* (large stone altars), *hare paenga* (boat-shaped houses), and *avanga* (rectangular stone cairns) are other examples of megalithic remains spread about the landscape. In order to fully understand the role that any of these types of megalithic structures may have played in the cultural evolution on Rapa Nui, the construction events for monuments must be dated with some accuracy.

However, dating all of the *moai* (or *ahu*, or *hare paenga*, etc.), or even an extensive sample of *moai*, can be a daunting task for several reasons. The statues themselves are monolithic constructions, and as such are not well suited for common chronometric dating techniques. Furthermore, with more than seven hundred statues remaining on the island, chronometric dating of contextual materials becomes a complicated, time-consuming, and extremely expensive prospect. Stevenson (1984) has applied the relatively inexpensive dating technique of obsidian-hydration to the fill materials, foundation, or associated materials of many *ahu*. Yet, a comparable approach to statues is not promising. While datable materials excavated from the fill or foundation of structures (i.e., *ahu*, *hare paenga*, *avanga*) can offer an approximation for the construction of architecture, the *moai* cannot be so firmly tied to contextual datable materials. Even though a *moai* may have once stood upon an *ahu*, there is no archaeological evidence to indicate that the construction or placement of the statue was contemporaneous with construction of the *ahu*.

Chronometric dating, however, is not the only method used by archaeologists to analyze artifact chronology. Artifact forms are often assumed to change over time, and seriation has been used by archaeologists for nearly a century to analyze chronological change in artifact form. Archaeological seriation is a method by which artifacts (or groups of artifacts) are arranged in a relative order to reflect formal variability that is ultimately attributable to a single common variable. This single, underlying variable could be social status, functional use, cultural tradition, or any number of cultural or environmental variables (Kuzara et al. 1966). In most cases however, seriation has been applied to examine formal differences among artifacts where the underlying variable is time. Thus, by arranging artifacts in a sequence to maximize similarity of nearby items, seriation creates an ordering that may, under certain conditions, reflect chronology.

Commonalities in Seriation

Despite the widespread application of seriation in Americanist archaeology, its methodological details and empirical results are often debated. Nonetheless, there are three general assumptions that seem to underlie seriation as a method to infer chronology from formal variability among artifacts.

The first assumption has to do with the nature of variation among the units (artifacts or groups of artifacts) to be seriated. Ford (1962) suggested that seriation would only be effective when change amongst units to be seriated was continuous and relatively gradual. Cowgill (1972:384) disagreed slightly with Ford's interpretation of the seriation method, replying that for the first assumption of seriation:

> …all that is required is that there never, among the set of units being seriated, be a break in the sequence so abrupt and catastrophic that units immediately following the break bear no (or only accidental) resemblance to units before the break.

Ford and Cowgill may have had similar interests in addressing the necessary historic continuity of units, but Cowgill had the advantage of seeing nearly a decade of mathematical literature on seriation to formalize assumptions for the method.

The second assumption for seriation in chronological analyses requires all units to be seriated to be of comparable temporal duration. Rouse (1967:162) made this assumption clear before Cowgill (1972). Rouse also made clear that units in a seriation should be regarded as events as opposed to objects. If the units to be seriated represent manufacture events for individual objects, there may be little doubt in the assumption that manufacture of each object spanned a similar amount of time. This assumption may be more important when the units to be seriated include multiple objects or groups of multiple objects.

The third assumption for seriation in chronological analyses is that, "in terms of the criteria of similarity used, trends of increasing dissimilarity over time indeed never reverse themselves" (Cowgill 1972:385). While this third assumption appears to be an observation about the nature of change, it is meant only as a requirement for the criteria of similarity used (Dunnell 1970:309). That is, the practitioner must employ criteria or variables (features, classes, etc.) such that those specific criteria or variables display a unimodal distribution over time, either in frequency values or in incidence (presence/absence). The unimodality requirement may, in some cases, simplify the iterative or trial-and-error process of ordering artifacts or groups to achieve the desired ordering. At the same time, however, the unimodality requirement places a greater burden on the practitioner to identify appropriate features or classes to be used as seriation criteria. The concept of unimodality is an important one, and has recently been discussed in the context of cultural transmission (Neiman 1995). Unimodality will be discussed further at a later point in this chapter.

There have been two kinds of seriation discussed most commonly in archaeological research: frequency seriation and occurrence seriation. According to Dunnell (1970:309),

> Frequency seriation arranges groups not only so that each class has continuous representation in the series of groups being ordered but also so that each continuous distribution exhibits the form of a unimodal curve in terms of the frequency of representation.

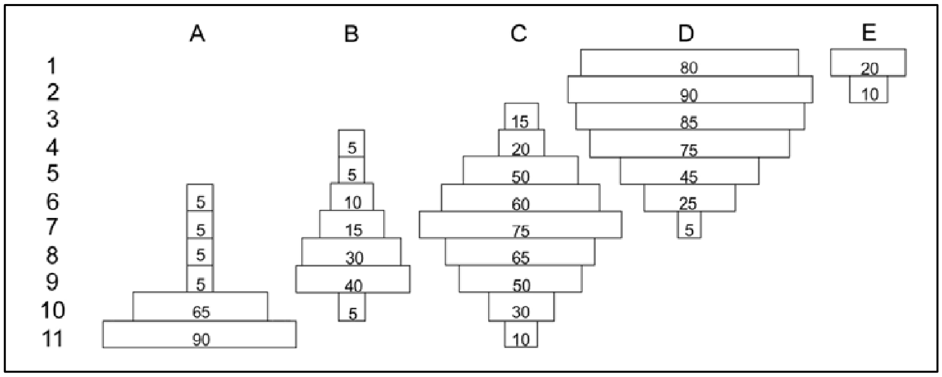


Figure 2.1. A successful frequency seriation orders assemblages (1-11) so that the relative abundance of each artifact class (A-E) displays a perfectly unimodal trajectory.

Figure 2.1 offers a graphic example of frequency seriation. Much of the discussion on seriation methodology, algorithms, and computer automation has evolved around seriation examples where unit values are originally expressed as frequencies or percentages (e.g., Ascher 1959; Ascher and Ascher 1963; Brainerd 1951; Hole and Shaw 1967; Kuzara et al. 1966; LeBlanc 1975; Meighan 1959; Robinson 1951).

On the other hand, archaeologists have demonstrated success with occurrence seriation as well (for examples in Oceania see Carson 2002; Cochrane 2002; Graves and Cachola-Abad 1996; McElroy 2003; Mulrooney 2004; Mulrooney and Ladefoged 2005). In occurrence seriation, the frequency of incidence or occurrence for a particular formal class within a particular unit is unimportant. Units to be seriated are ordered based solely on the presence (alternatively labeled “1”) or absence (alternatively labeled “0”) of classes. Occurrence seriation arranges units so that throughout the ordering, the “1’s” in each class are not interspersed with “0’s” in the same class. Figure 2.2 offers a graphic example of occurrence seriation.

	A	B	C	D
4	1	1	1	1
2	1	1		
5		1	1	1
1	1			
6			1	1
3	1	1	1	
7				1

-->

	A	B	C	D
1	1			
2	1	1		
3	1	1	1	
4	1	1	1	1
5		1	1	1
6			1	1
7				1

Figure 2.2. The table on the left shows unordered data divided into units (1-7) based on the presence or absence of classes (A-D). The table on the right shows the same units organized into a perfect occurrence seriation, where "1's" are not interspersed with blanks or "0's".

Several publications have made cautionary statements for the application of occurrence seriation (e.g., Cowgill 1968; Hole and Shaw 1967; Lipe 1964). Cowgill (1968:518) states:

> One trouble with presence-absence as pointed out by [Hole and Shaw] and by Lipe…is that even slight mixing between units will have serious results…Presence-absence makes sense only when we feel sure that absence in the collection means that the trait was *really* absent (not just rare) in whatever entity the collection has sampled.

In other words, while two units that are composed of 4% and 94% of a particular class are distinguishable in frequency seriation, the same units judged by the same class are identical in occurrence seriation (both units obtain a "present" or "1" value for that particular class). Equally problematic, two units that are composed of 0% and 4% of a particular class are distinguishable in frequency seriation with their similarity in frequency value rather than dissimilarity being of most importance. However, these two units obtain opposing values ("1" and "0" respectively) in occurrence seriation.

The problems for occurrence seriation discussed by Cowgill and others limit, but do not completely eliminate the usefulness or potential applications of occurrence seriation.

Seriating Rapa Nui Statuary

The goal for this dissertation is to seriate a particularly challenging set of artifacts—prehistoric statues of Rapa Nui. Chapter 3 presents a seriation analysis of statuary using the optimal path seriation (OPS) technique developed by Shepardson and Shepardson (2004a). An axiomatic mathematical derivation of the technique is presented in Appendix A. The technique was developed to address four specific challenges presented by the Rapa Nui statuary dataset. These challenges include (1) sample size; (2) classification of statuary; (3) scale or resolution of the temporal analysis; and (4) absolute dating of statuary in addition to relative dating.

Sample Size

Chronological seriation may be a relatively simple concept, but the application of the concept is often time-consuming and cumbersome. Iterative or repetitive procedures within a seriation algorithm make working by hand confusing—especially as the number of units and criteria included in the seriation increases. The database of Rapa Nui statuary includes 712 statues and twenty-two formal variables that might be considered as seriation criteria. Therefore, any seriation procedure of statuary may have to search millions of possible orderings of hundreds of statues in order to reach optimal results. This task requires tremendous computing power and is well beyond the realm of possibility to perform by hand.

In an effort to accommodate large data sets and expedite analysis of such data, archaeologists and colleagues in mathematics and computer sciences have produced algorithms to automate complicated seriation procedures. Furthermore, these algorithms have often been implemented in computer programs.

Beginning with Robinson (1951), archaeological analyses began to conceptualize seriation as a matrix-ordering problem. Frequency values for different units and classes were recalculated as "agreement coefficients" in a similarity matrix or table. Agreement coefficients reflect the total similarity between each pair of units to be seriated in terms of unit frequency values for each class or criterion in the seriation. Robinson (1951:298) explains that for the agreement coefficients or "totals":

> …if the deposits are chronologically arranged along the margins of the table, the totals for the rows or columns will show a pattern also. Beginning at either end of the chronologically ordered series, the totals will rise progressively to a maximum, and then will decrease progressively to a minimum at the other end of the series.

Between the 1960's and 1970's, *American Antiquity* published a variety of articles that continued to conceptualize seriation in terms of the matrix-ordering problem that Robinson identified. Marquardt (1978) offers an excellent synthesis of several of the efforts to improve techniques within seriation within this time period. Many of the algorithms proposed to solve the matrix-ordering problem were accompanied by, or drew upon existing software, to implement the specific algorithm (e.g., Ascher and Ascher 1963; Bordaz and Bordaz 1970; Cowgill 1972; Craytor and Johnson 1968; Dempsey and Baumhoff 1963; Gelfand 1971; Goldmann 1971; Hole and Shaw 1967; Kuzara et al. 1966; Landau and de la Vega 1971; Renfrew and Sterud 1969).

Matrix-ordering procedures have implemented highly sophisticated mathematical techniques to search for and successfully find solutions. At this point, matrix-ordering procedures are likely to improve more from continuous improvements in computing power than from any methodological discovery.

There has, however, been a slightly different manner of conceptualizing the seriation problem. Meighan (1959) and his “3-pole method” may have offered the first crude conceptualization of seriation as a “path” problem. Meighan suggested that frequency values for three classes (or combinations of more classes grouped to form just three classes) and any number of units to be seriated could be plotted on a three-pole graph (see Figure 2.3). Meighan (1959:204) explains, “A line is drawn through the scattered points so that there are as many points on one side of the line as the other.” Furthermore, by projecting each data point perpendicularly to the nearest point on the line, Meighan concluded that the units could be ordered chronologically along a linear path.

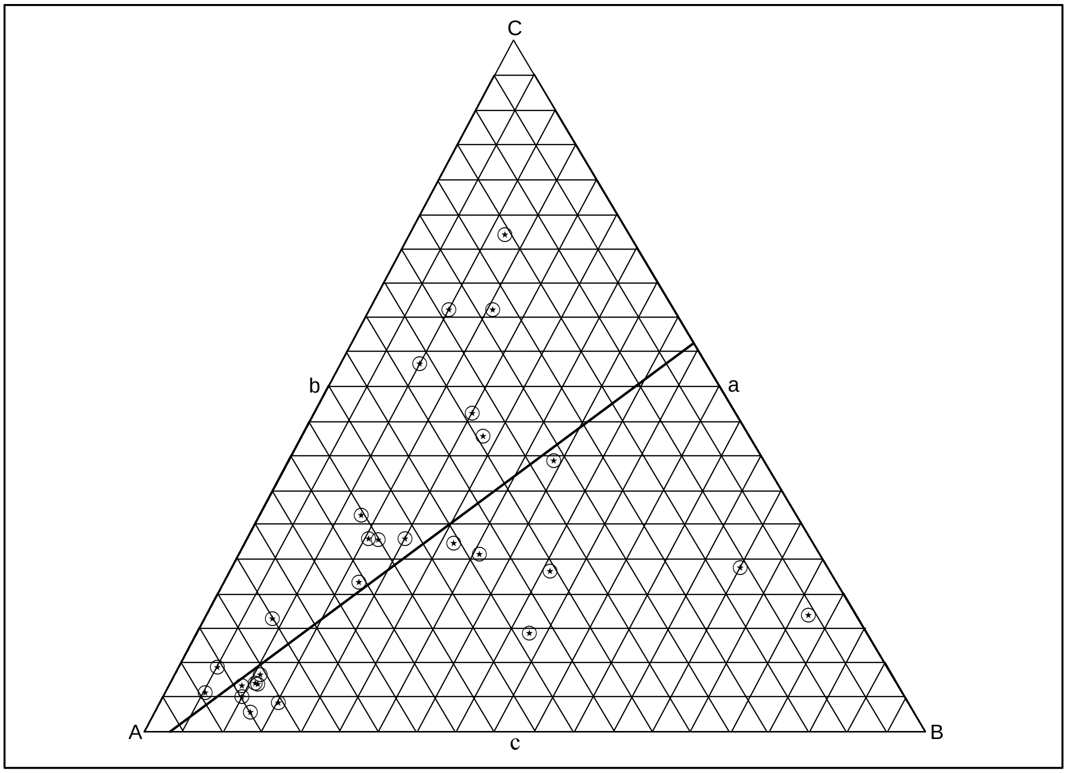


Figure 2.3. In Meighan's (1959) 3-pole method, seriation units are plotted on a 3-pole graph according to values for seriation criteria (a, b, c) and a line is drawn so that an equal number of points reside on each side of the line.

Meighan claims his 3-pole approach to be successful based on a comparison of a subset of seriated units to dendrochronological dates. Cowgill (1968:519), Hole and Shaw (1967:69-77), and Marquardt (1978:272) have also noted that despite its simple appearance, Meighan's 3-pole approach generally reaches comparable or even better results than other more complex procedures.

Even with its successes, Meighan's path approach requires critical review. Meighan admits that if all three of the plotted classes are simultaneously changing with respect to time, a curve rather than a straight line must be used to divide the points into equal halves. Meighan (1959:204) offers the more simplistic example where a straight line is drawn rather than a curve, suggesting that, "A mathematical way of plotting such a curve is not yet available." Unfortunately, infinitely many different lines or curves could be used to divide the plotted points into equal haves, and many of these lines would result in different chronological orderings of units to be seriated. Meighan, however, offers no detailed objective approach to choose between potential lines or curves. Finally, it should be noted that by projecting plotted points perpendicularly onto a line or curve, the practitioner is ultimately discounting variation in at least one of the three classes. The purpose of illuminating potential weaknesses in Meighan's exposition of the 3-pole approach in seriation is not to discredit the concepts that he proposes, but rather use them to advance the path approach in seriation that Meighan pioneered.

The 3-pole approach is particularly innovative and useful in two aspects. First, Meighan demonstrated how information or values from a given class-space can be plotted in multiple dimensions, and by doing so we can envision the distance between any two points in *n*-space to reflect the dissimilarity between the two units represented by those points. Meighan's work also suggests that time can be represented in the same *n*-space model as a curvilinear path.

Although Ascher (1959) attempted to improve upon Meighan's 3-pole seriation procedure, most archaeological research related to seriation throughout the 1960's focused on the Robinson matrix-ordering concept rather than the path concept. Nearly a decade after the work of Meighan and Ascher, archaeologists realized a mathematical relationship between the matrix-ordering concept and the path concept. The path that best orders frequency values for *n* classes in a chronological seriation may be conceived of as the “minimum path” in *n*-space (see Appendix for mathematical derivation). Marquardt (1978:277-278) states that,

> A number of individuals have used minimum path approaches to the seriation problem. Wilkinson (1971, 1974) realized that the question of rearranging an incidence matrix with the intention of bunching the 1’s together as closely as possible in each column is analogous to the classic graph theoretic question known as the Traveling Salesman problem (Bellmore and Nemhauser 1968). Although the problem has not been “solved”—that is, no nonexhaustive algorithm has been discovered that will find *the* shortest tour for a salesman starting from a given city, visiting each of a specified group of cities, then returning to the origin of the tour—heuristic search techniques are known that provide good estimates for the solution.

While the mathematics and details behind the minimum path approach may be daunting, the concept may have a rather intuitive graphic representation (see Figures 2.4, 2.5, and 2.6). The optimal path seriation technique (implemented through the *OptiPath* software), conceptualizes the seriation problem as a path or Traveling Salesman problem.

Table 2.1. Example applications of OPS algorithm and *OptiPath* software.

Reference	Artifact	Seriation	No. Units	No. Criteria	Solution Time
Brainerd (1951)	Pottery	Frequency	8	8	1 sec.
Marquardt (1978)	Lighting	Frequency	11	5	1 sec.
Shepardson (2006)	Hypothetical	Frequency	30	10	10 sec.
Harrington (1954)	Pipes	Frequency	5	6	<1 sec.
Dunnell (1970)	Hypothetical	Occurrence	6	5	<1 sec.
Shepardson (2006)	Hypothetical	Occurrence	50	35	9 sec.

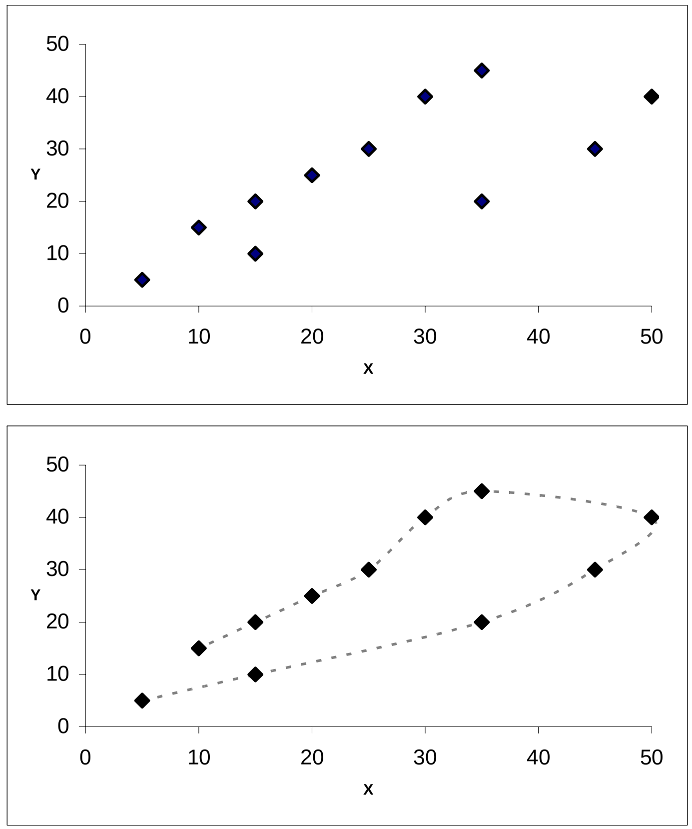
The exposition of results in Table 2.1 demonstrates the effects of better algorithms and faster computers over the years. This should help to convince archaeologists that there is little reason *not* to attempt seriation analysis in conjunction with other archaeological methods. While Cowgill (1968:518) once predicted that, "It would take years or millennia for any foreseeable computer to try every order for a dozen or more units," the *OptiPath* software on a personal computer can "find" near optimal results for 50 units and 35 classes in just 9 seconds!

Classification of Statuary

The formal variability amongst statues on Rapa Nui offers great opportunity for seriation analysis. Previous attempts to analyze formal variability in Rapa Nui statuary are discussed in Chapter 3, but it is important to note, at this point in the analysis, that efforts to classify statues into formal types that reflect time have been unsuccessful. Through correlation tests and cluster analyses, Van Tilburg (1986) identifies seven nominal formal types of statues which she attempts to associate with Stevenson's (1986) *ahu* phases. Unfortunately, subsequent research (Skjølsvold 1993:93) suggests that, "No chronology is however, obtained in this way (cf. Van Tilburg 1986:360, table 28)." Despite extensive research on statue form and variability, archaeologists have yet to systematically identify classes that adequately represent temporal units (Liller 1993b; Van Tilburg 1986, 1993, 1996). Thus, one of the major difficulties in seriating Rapa Nui statuary becomes the construction or identification of temporal classes.

Unit	X	Y
0	5	5
6	30	40
1	15	10
8	20	25
2	35	20
3	45	30
10	10	15
5	35	45
7	25	30
4	50	40
9	15	20

(a)



(b)

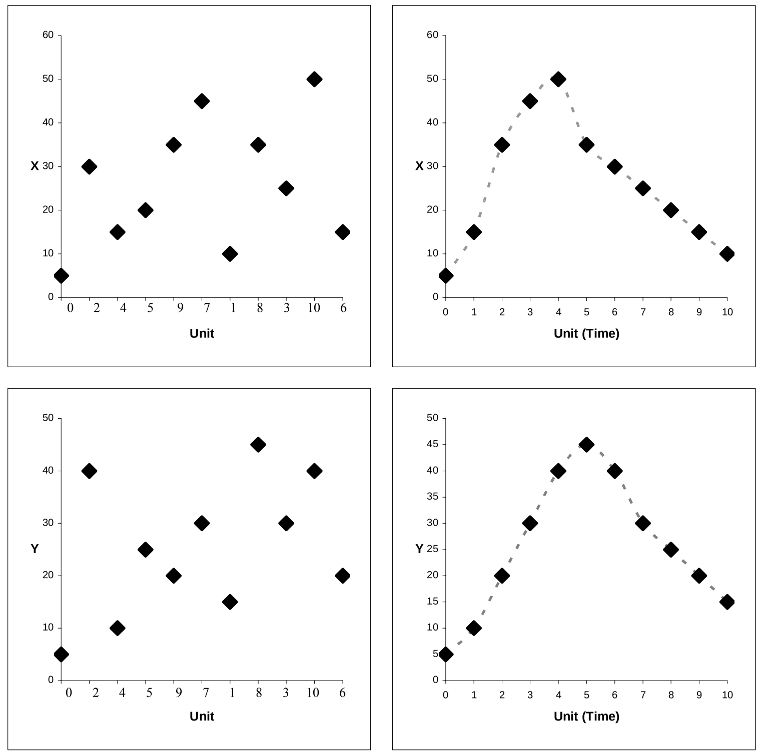
Unit	X	Y
0	5	5
1	15	10
2	35	20
3	45	30
4	50	40
5	35	45
6	30	40
7	25	30
8	20	25
9	15	20
10	10	15

(c)

Figure 2.4. For seriation units 0-10 (a), optimal path seriation considers those units as points in *n*-space (b:top) where *n* is the number of seriation criteria. OPS then searches orderings of artifacts to find the path passing through all points such that the sum of the slope of the path for all segments between points is minimized (b:bottom). The ordering of units along this path (c) is assumed to reflect chronology, although without additional information the practitioner cannot distinguish which end of the chronology is earlier and which is later.

Unit	X	Y
0	5	5
2	15	10
4	35	20
5	45	30
9	50	40
7	35	45
1	30	40
8	25	30
3	20	25
10	15	20
6	10	15

(a)



(b)

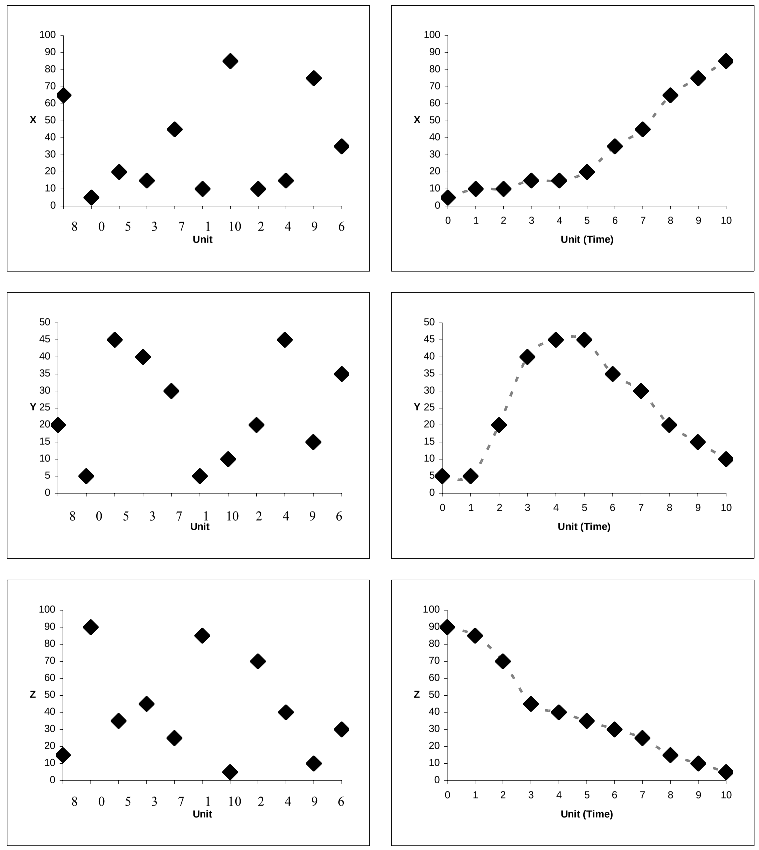
Unit	X	Y
0	5	5
1	15	10
2	35	20
3	45	30
4	50	40
5	35	45
6	30	40
7	25	30
8	20	25
9	15	20
10	10	15

(c)

Figure 2.5. An equivalent conceptualization of the OPS algorithm considers each seriation criterion separately. That is, OPS begins with a random ordering of seriation units (a). Alternative unit sequences are tested to find the ordering such that the sum of all slopes for all segments between points for all seriation criteria is minimized. Compare the random unit sequence (b:left) to the "paths" created for each individual seriation criterion (b:right). The resulting ordering (c) is assumed to reflect chronology.

Unit	X	Y	Z
8	65	20	15
0	5	5	90
5	20	45	35
3	15	40	45
7	45	30	25
1	10	5	85
10	85	10	5
2	10	20	70
4	15	45	40
9	75	15	10
6	35	35	30

(a)



(b)

Unit	X	Y	Z
0	5	5	90
1	10	5	85
2	10	20	70
3	15	40	45
4	15	45	40
5	20	45	35
6	35	35	30
7	45	30	25
8	65	20	15
9	75	15	10
10	85	10	5

(c)

Figure 2.6. The same principles from Figure 2.5 apply to optimal path seriation analysis of data sets with 3 or more criteria.

Seriation practitioners have often encountered problems defining appropriate (temporal) classes, and there has been some attempt to simplify the seriation process by using variables other than classes as the criteria for seriation (e.g., LeBlanc 1975; Marquardt 1974). LeBlanc included the metric variable "Line Width (mm)" to describe one particular aspect of pottery decoration in seriation analyses. And Marquardt incorporated what he referred to as "ratio-scale variables", or a ratio of two metric variables, as seriation criteria.

The fact that LeBlanc and Marquardt are able to successfully seriate archaeological collections based on metric variables or criteria makes a substantial contribution to theoretical discussions regarding seriation. Their work suggests that changes in measurable (or metric) variables of artifact form may exhibit similar quantitative patterns to changes in class frequencies of artifacts. This result may be particularly relevant to a seriation analysis of Rapa Nui statuary. These artifacts have been described systematically in terms of metric variables by several researchers (Riquelme 1991; Shepardson 2005a; Van Tilburg 1986). Any direct analysis of metric statuary data can offer greater precision when compared to an analysis of classes abstracted or generalized from the raw metric data.

LeBlanc and Marquardt are not the only archaeologists to realize that certain metric variables demonstrate non-random patterns of change over time. Both Braun (1977, 1985) and Neiman (1995) observed that wall thickness (measured in millimeters) of Woodland ceramics declined gradually over a matter of centuries. Similarly, Harrington (1954) observed a general decline in the hole diameter of stems from clay tobacco pipes over a span of 180 years.

The optimal path seriation algorithm and *OptiPath* software employed to analyze formal variability in statuary in Chapter 3 build upon the observations and work of LeBlanc, Marquardt, Harrington, Braun, Neiman, and others. Optimal path seriation allows practitioners to directly analyze metric data, assuming that values of metric variables change gradually over time. This assumption may be analogous to Cowgill's (1972:384) stipulation that seriation units must demonstrate a sequence of formal similarity without severe interruptions. Mathematical constraints for this assumption in the optimal path seriation algorithm are presented in Appendix A.

Resolution of Temporal Analysis

LeBlanc and Marquardt both demonstrate the successes of their innovative approaches to selection of seriation criteria. However, the variables that they used for seriation criteria in place of traditional classes may have only made the seriation process more difficult for the archaeologist. Marquardt (1978:261) suggests that constraints on the variables used as seriation criteria in his analysis might be even more restrictive (monotonic rather than unimodal) than on classes, "The variables are chosen in such a way that they either generally increase or generally decrease with the passage of time." Of course, if it is known ahead of time that a variable changes monotonically with respect to time, there may be little need for any real seriation "procedure". LeBlanc, similarly, restricts his seriation approach to "micro-seriation" or assemblages representing a relatively short period of time. Presumably, this restriction is made to ensure short-term simplicity among variables employed as seriation criteria. Ultimately, the "leap" that

LeBlanc and Marquardt make from classes to formal features or variables (metric or otherwise) as criteria for seriation does little to facilitate or expedite the seriation process.

The requirement for all seriation criteria to demonstrate unimodal (or more restrictive) temporal patterns, whether criteria are classes or metric variables, limits the practitioner either in the selection of seriation criteria or in the temporal scope/duration of analysis. The unimodality requirement, however, is also related to the temporal resolution of the analysis. And in some cases, restricting seriation criteria to those classes or variables that demonstrate unimodal patterns may be an inappropriate theoretical constraint on seriation analyses.

The concept of unimodality has played a major role in seriation history, constraining matrix-ordering techniques and also constraining the process of class formation for seriation analyses. Computer simulation of cultural transmission processes has offered some justification (although the relationship is indirect) for the unimodal temporal trend in class distributions that has structured seriation analyses for so long (Neiman 1995). It is clear from the computer simulations that Neiman presents that changing class frequencies, modeled over time as a process of innovation and selectively neutral variation (drift), do *not* display perfectly unimodal trends (Neiman 1995:12). Unimodal (or lenticular, battleship-shaped, etc.) patterns that archaeologists have often identified in seriation analyses may be due to the combined effects of cultural transmission processes *and* imprecision in archaeological sampling rather than cultural transmission processes alone (Neiman 1990). Archaeological collections or samples that compose units of analysis within a seriation often span a period of time such that short

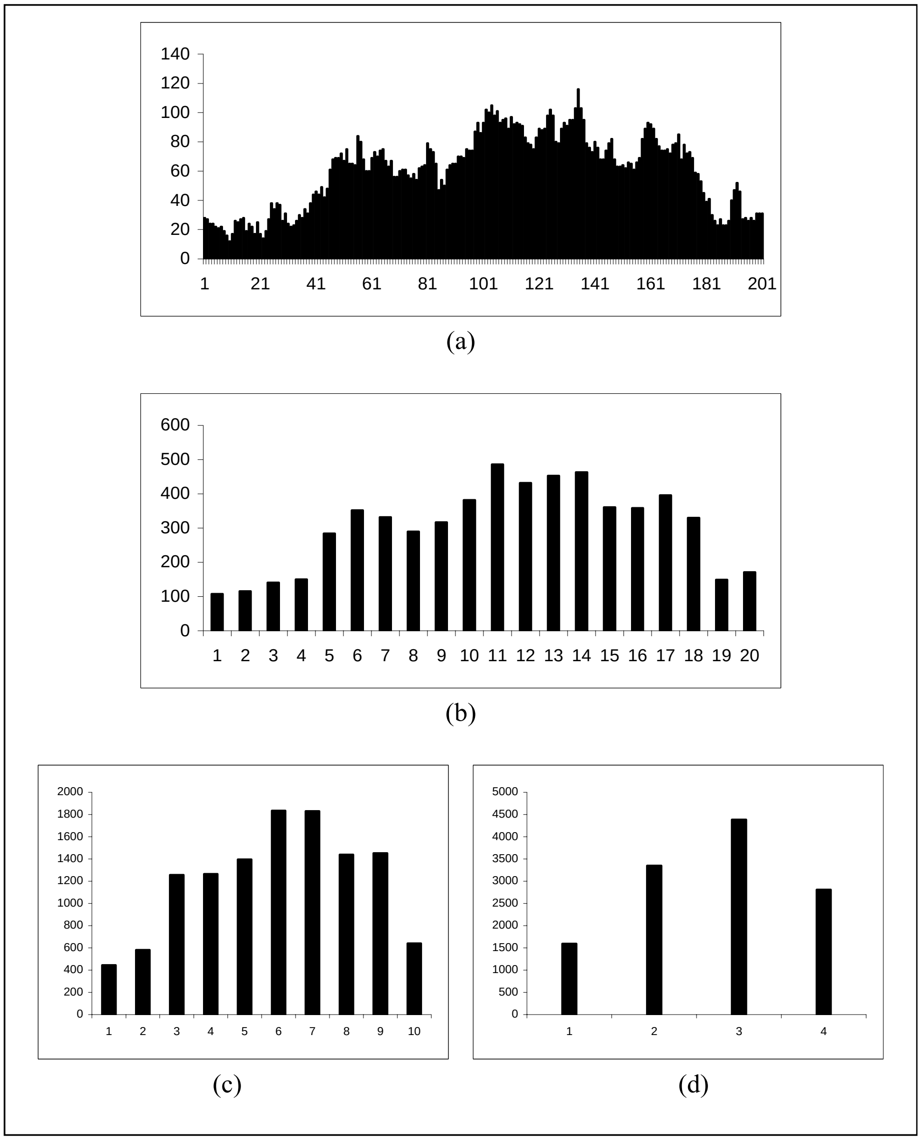


Figure 2.7. Typical patterns for cultural "variants" in Neiman's (1998) simulation of cultural transmission processes are not unimodal when examined at finer levels of temporal resolution but may take on a unimodal appearance as artifact collections are aggregated over longer time periods. In (a), simulation results for the abundance of a single cultural variant are displayed by yearly values over a span of 200 years. In (b), simulation results are displayed as aggregate abundances for every 10 years. In (c), simulation results are displayed as aggregate abundances for every 20 years. In (d), simulation results are displayed as aggregate abundances for every 50 years. As temporal resolution decreases, multimodal patterns attributable to stochastic processes in cultural transmission are "averaged out" to form unimodal patterns.

term fluctuations related to stochasticity in cultural transmission processes are “averaged out”. Consequently, the time-averaged data appears to follow a predictable, unimodal pattern (see Figure 2.7).

The goal in the seriation analysis of Rapa Nui statuary in Chapter 3, however, is an object-scale analysis (i.e., the construction of an individual statue represents a single event or seriation unit). In an object-scale analysis, there may not be any time-averaging of data. Each object may represent the fruition of a cultural transmission event. As a general rule, the more faithfully the units of seriation reflect individual cultural transmission events (rather than time-averaged combinations of events) the less appropriate the unimodality restriction on seriation criteria may be. In an object-scale analysis, the practitioner might expect multimodal patterns among seriation criteria (associated with the stochastic processes of transmission).

The optimal path seriation algorithm and *OptiPath* software were developed to accommodate multimodal or complex patterns in variables used as seriation criteria. Optimal path seriation stipulates only that seriation criteria must be chosen so that two identical units (as defined by seriation criteria) within the seriation do not represent two distinct points in time. Relaxing the unimodality requirement for individual seriation criteria may: (1) make selection of seriation criteria easier by expanding the number of eligible variables; (2) allow seriations employing criteria other than classes to cover longer periods of time; and (3) offer more appropriate theoretical constraints in object-scale seriation analyses.

Absolute Dating

The seriation method is commonly used in archaeological analyses to develop a relative ordering of artifacts (or groups of artifacts) that reflects chronology. Frequently, a relative ordering of artifacts will not suffice for detailed archaeological analysis. In many studies, seriation practitioners are able to calibrate distinct units of seriations to absolute chronometric dates through stratigraphic or other contexts.

On the other hand, there are many collections of artifacts that cannot be so easily dated by contextual remains. Subjecting prehistoric Rapa Nui statuary to a seriation analysis and determining a relative chronological ordering of megalithic statuary certainly provides original insight for the Rapa Nui prehistoric sequence. At the same time, however, a relative sequence of statue construction may lack critical chronometric information. Thus, the goal of the seriation analysis in Chapter 3 is to develop an object-scale ordering of Rapa Nui statuary with reference to absolute dates.

The optimal path seriation technique, by assuming a relatively constant and gradual rate of change, offers the practitioner the potential to calculate absolute dates for all seriation units (or events). In all cases, however, the practitioner must provide known dates for at least two of the units to be seriated (e.g., oldest and youngest). Several analytical techniques before optimal path seriation have been based on an assumption of constant and gradual rates of change. Archaeologists have appealed to this assumption with some regularity in analyses of cultural transmission phenomena (e.g., Binford 1962; Dempsey and Baumhoff 1963:507; LeBlanc 1975:35; Plog and Hantman 1990:444).

Other archaeologists have argued against the assumption of constant and gradual rates of change (e.g., Drennan 1976; O'Brien and Lyman 1999). Ultimately, whether rates of change were constant or gradual may be an empirical issue and vary from study to study. Regardless, the assumption that rates of change are, or were, constant and gradual may provide a useful starting point in attempting to attribute absolute dates to units or events in a seriation analysis.

Seriating Ford Mustangs

Testing the OPS algorithm and *OptiPath* software on archaeological artifacts is difficult because the precise manufacture dates for large groups of archaeological remains are rarely known. Therefore the seriation technique is first tested on data for Ford Mustang automobile models manufactured between 1964 and 2000 published by Ilaria (1999). Four formal variables were selected from the automobile data as seriation criterion (see Table 2.2): (1) the number of different exterior colors offered for a particular model/year; (2) the number of different types of engines offered for a particular model/year; (3) the minimum horsepower engine available to the consumer for each model/year; and (4) the maximum horsepower engine available to the consumer for each model/year. These variables were selected because data were available for all models/years and variability existed from one year to the next. All four of these seriation criteria can be considered as features rather than classes.

Table 2.2. Data for Ford Mustang automobile models between 1964 and 2000.

Model/Year	Colors	Engines	Min HP	Max HP
1964	17	3	101	210
1965	17	4	120	271
1966	23	4	120	271
1967	28	5	120	320
1968	16	7	120	390
1969	17	9	115	390
1970	16	7	115	390
1971	18	8	145	375
1972	16	5	98	275
1973	16	4	99	266
1974	14	2	88	105
1975	15	3	88	140
1976	15	3	88	140
1977	13	3	92	134
1978	14	3	88	139
1979	15	5	85	140
1980	15	5	88	132
1981	14	3	88	120
1982	14	4	88	157
1983	14	4	88	175
1984	11	6	88	175
1985	11	5	88	210
1986	12	4	88	205
1987	12	2	88	225
1988	11	2	88	225
1989	11	2	88	225
1990	11	2	88	225
1991	10	2	105	225
1992	11	2	105	225
1993	9	3	105	235
1994	11	3	145	240
1995	11	4	145	300
1996	10	2	150	215
1997	10	2	150	215
1998	10	2	150	250
1999	10	2	190	260
2000	10	2	190	260

Figure 2.8 displays a comparison of the actual chronological ordering for Ford Mustang models and the ordering computed through OPS analysis. All points falling

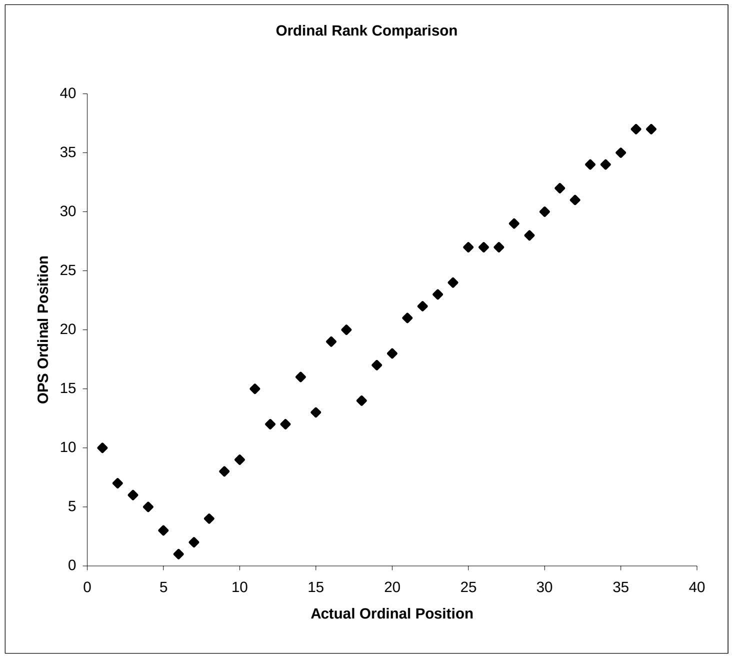


Figure 2.8. Comparison of actual Mustang chronological ordering and OPS analysis ordering (R^2=0.94).

precisely on a diagonal would indicate a flawless ordering by the *OptiPath* software. In this case, the OPS ordering shows little difference from the actual ordering (R^2 = 0.94). The major source of discrepancy comes from the first five models/years where OPS has reversed the correct ordering of Mustang models. On average, the ordinal position error is 5% (1.84 ordinal positions out of 37).

These results suggest that the four formal variables isolated for seriation analysis closely adhere to the conditions set forth in the OPS objective function. Thus, the *OptiPath* software successfully identifies the "paths" that formal variable values follow through time (see Figure 2.9). Furthermore, the analysis demonstrates the potential of OPS to seriate artifacts based on metric data and non-unimodal seriation criterion.

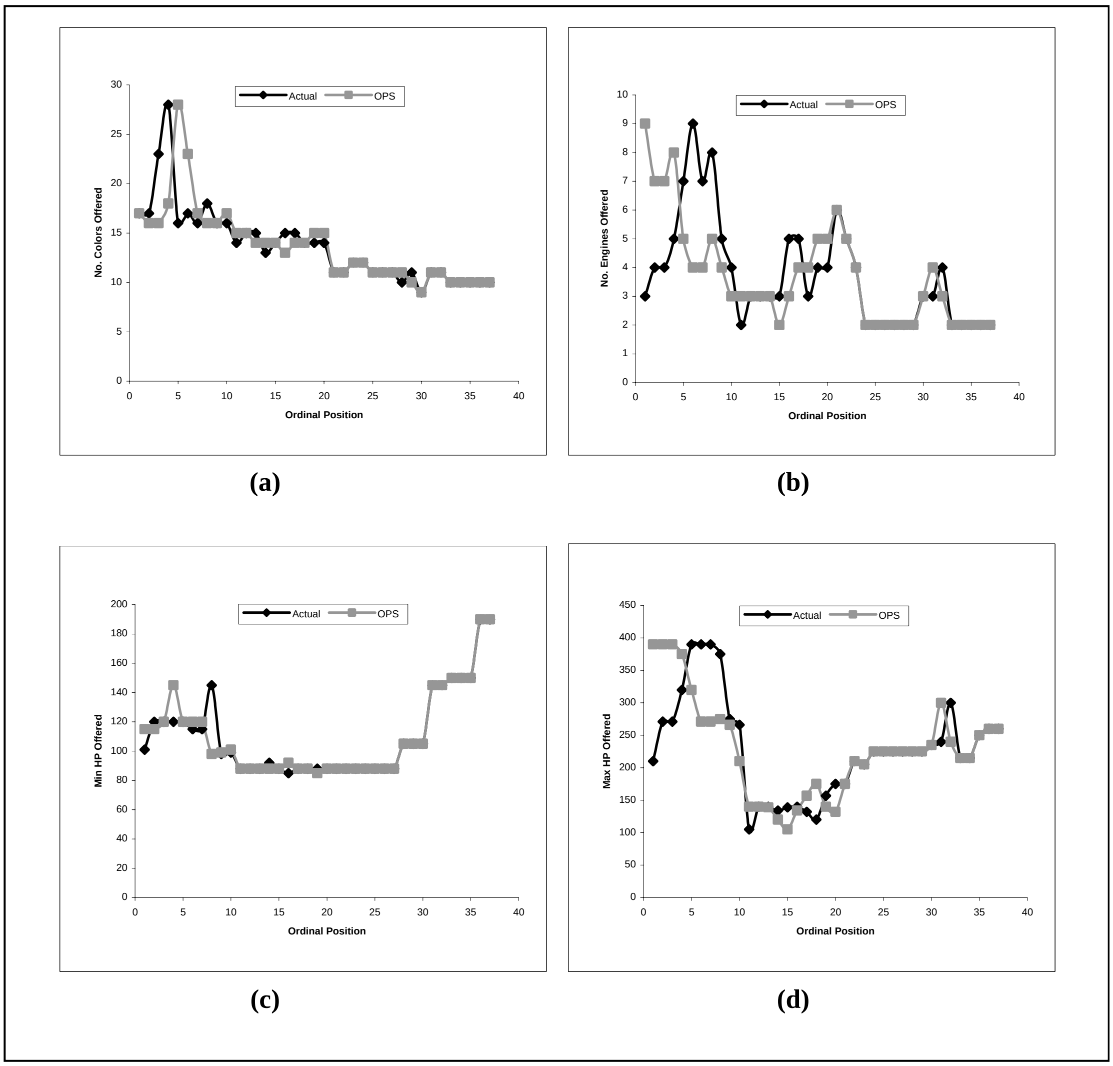


Figure 2.9. Actual and OPS "paths" that formal variable values follow over time.

Despite this success, ordinal rankings are of limited application in many archaeological settings. Assigning dates to specific artifacts is often the ultimate goal in a chronological analysis. The *OptiPath* software assigns dates to individual artifacts in a chronological ordering based on the degree of (dis)similarity from one artifact to the next. Effectively, this dating mechanism relies on the aforementioned condition of a constant rate of change in form over time. While this may not be true in all cases, a constant rate of formal variation appears to be a reasonable assumption for Ford Mustangs. Using *OptiPath* to assign dates to each model/year in the seriation analysis, an average error of 11% (4 years out of 37) is achieved. Figure 2.10 displays the similarity between actual dates for Mustang models and dates assigned by OPS (R^2 = 0.86). This level of accuracy may be comparable to or even exceed popular chemical dating techniques in archaeology.

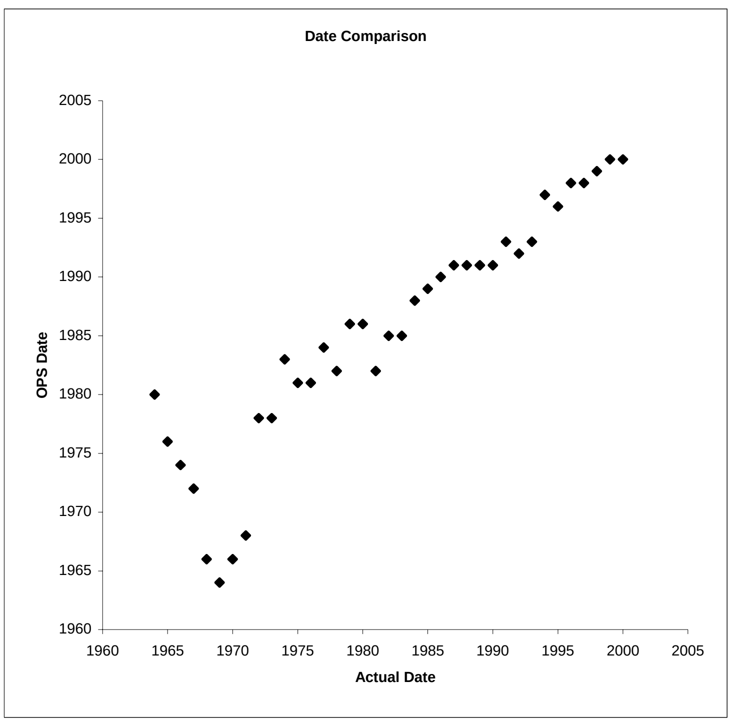


Figure 2.10. Comparison of Mustang manufacture years and OPS analysis years (R^2=0.86).

The success of the Ford Mustang analysis lends confidence to the OPS seriation approach. However, there are a few points worth noting that may make chronological analysis of Mustangs a unique problem. First, this data set may be considerably smaller than many archaeological collections. Consequently, absolute errors (and possibly our relative orders) for larger datasets may decrease (because small samples are more prone to larger variance). Second, data is more reliable and distributed more regularly across time (i.e., yearly models) than we are likely to encounter in a true archaeological study. Nevertheless, the Mustang analysis demonstrates the potential to frame studies of formal or stylistic variation in artifacts as a constrained mathematical optimization problem. Extensive repeated applications of OPS to "control" data sets like automobile models is one way to determine the general applicability of the model to artifact analysis.

Hypothetical Data

Another manner in which the general applicability of OPS may be demonstrated is to test the model on two hypothetical datasets specifically designed to push the OPS algorithm to its limits. The hypothetical datasets are composed of 100 artifacts whose manufacture dates are selected randomly from a uniform distribution between AD 1001 and 2000. Each individual artifact is described by five formal variables. Each formal variable's values follow (with some degree of "noise") a path that is defined by a constant, linear, quadratic, reciprocal or sinusoidal function respectively. The first hypothetical dataset includes 5% noise for each formal variable value so that variable values only approximate the underlying path (rather than follow it precisely) over time.

Under these complex conditions, OPS performs only slightly worse than with the Ford Mustang analysis. The OPS ordinal rankings for artifacts, on average, differ from the correct ordinal rankings by 16% (16 ordinal positions out of 100). The OPS dates for artifacts, on average, differ from the correct dates by 15% (151 years out of 1000).

The applicability of the OPS approach was further tested by increasing our noise factor to 10% in the second hypothetical dataset. By doing so, the path that each formal variable's values follows over time becomes increasingly difficult to identify. This may be reflective of a group of artifacts for which each artifact was only loosely representative of the previous artifact's form. Or, alternatively, the "noise" term may reflect a group of artifacts for which data collection may be difficult and include considerable imprecision. Again, OPS results worsen slightly. The OPS ordinal rankings for artifacts, on average, differ from the correct ordinal rankings by 20% (20 ordinal positions out of 100). The OPS dates for artifacts, on average, differ from the correct dates by 22% (222 years out of 1000).

The results from OPS analysis of Mustangs and hypothetical data suggest that the OPS technique may be reliable, but accuracy of results depends on the size, complexity, and "noise" of the dataset. Unfortunately, these are relative factors that cannot easily be distinguished in real datasets.

Dress Fashion

So far, the OPS procedure has been tested for cases in which the only information considered comes from formal variable values. In an archaeological setting, however, excavation, stratigraphy, dendrochronology, chemical dating, and comparative artifact assemblages may also provide information relevant to a chronological analysis.

One additional application of OPS is presented here to demonstrate how OPS analysis may be effectively informed and improved by limited supplementary chronometric information. Richardson and Kroeber (1940) present dress fashion data that spans 150 years (1787 to 1936 with two years' data missing). Yearly dress fashion is defined in the data set by six formal variables (length of skirt, length of waist, length of décolletage, width of skirt, width of waist, and width of décolletage). Using these six variables to order dress fashions chronologically, the OPS ordinal rankings, on average, differ from the correct ordinal rankings by 29% (43 ordinal positions out of 148). The OPS dates, on average, differ from the correct dates for dress fashions by 33% (49 years out of 150).

As a comparison, three dress fashion years were randomly selected from dispersed locations in the chronology. Using precise dates to anchor these three fashions to their actual corresponding years, results improved considerably. After running the OPS analysis five times with three "anchors" chosen randomly each time, the ordinal ranking error improves to, on average, 20%, and the dating error improves to, on average, 19%.

A similar comparative analysis included five "anchors" or control points in the OPS analysis. Again, the analysis was executed five times to assess an average improvement in both ordinal and dating errors. In this case, the ordinal ranking error improves from the initial 29% to 16%. The dating error improves from the initial 33% to 16% as well.

Thus, while large or "noisy" data sets may present challenges for OPS, some of the adverse effects in a chronological analysis may be countered by anchoring (or including dates for) just a few specific artifacts throughout the chronological sequence in the OPS analysis. This may be a cost- and time-effective approach to chronological analyses of large assemblages of artifacts for which dates (or even date ranges) are known for a small subset of artifacts.

Discussion

Optimal path seriation has been developed for the particularly challenging task of dating Rapa Nui statuary. The OPS implementation with *moai* data offers an empirical contribution as the first extensive, detailed analysis of statue chronology. While it may be impossible to know precisely the accuracy OPS will have when applied to statue data, the preceding analyses offer some indication. Table 2.3 summarizes OPS performance on data sets described in this chapter. The Ford Mustang data, the hypothetical data, and the dress fashion data offer some justification for application of the OPS approach and *OptiPath* software. Continued empirical testing of OPS will further determine its reliability and help to further refine the search algorithm to provide optimal dating results.

The OPS model, which has been derived axiomatically, may also offer a theoretical contribution by bringing us one step closer to a general "theory" of seriation (current seriation techniques can be shown to be special cases of optimal path seriation –

Table 2.3. Summary of results for OPS analyses.

Data Set	Anchors	Artifacts	Years	Average Ordinal Error (percentage)	Average Ordinal Error (positions)	Average Dating Error (percentage)	Average Dating Error (years)
Ford Mustangs	0	37	37	5	2	11	4
Hypothetical - 5% Noise	0	100	1000	16	16	15	151
Hypothetical - 10% Noise	0	100	1000	20	20	22	222
Dress Fashions	0	148	150	29	43	33	49
Dress Fashions	3	148	150	20	30	19	29
Dress Fashions	5	148	150	16	24	16	24

see Appendix A). As Lewontin (1974) suggested for the field of evolutionary biology and Dunnell (1980) extended to the field of archaeology, there are three requisites of a compelling scientific theory.

First, the theory must be adequately comprehensive and internally consistent with its explanatory variables to rationalize observed phenomena (*dynamic sufficiency*). OPS is a mathematically-oriented approach to one of archaeology's oldest methods, seriation. Appendix A explicitly states the assumptions of the model and demonstrates the theoretical rigor of the approach through an axiomatic derivation. Although the assumptions and details of the OPS derivation may appear unorthodox to some, the traditional occurrence and frequency seriation techniques are shown mathematically to be special (and arguably suboptimal) cases of the OPS approach. Historically, seriation analyses have been characterized by empirical success rather than theoretical insight (Dunnell 1997; Lipo et al. 1997). However, by exposing a general mathematical link among different techniques in seriation, OPS establishes a new level of internal consistency.

Second, the theory must use variables that have a representation or measurability in the contemporary physical world (*empirical sufficiency*). OPS ensures that formal variables have a real representation (and one that practitioners can agree upon) by using metric data to seriate artifacts. A large portion of archaeological data is often collected in metric form. Even descriptions or data that are not explicitly metric may be based implicitly on metric units (e.g., we might call an artifact "rectangular" or "red", but these descriptions are loose interpretations of an item's length-to-width ratio and/or internal angles, or spectral wavelength respectively). Metric data is especially useful because archaeologists can usually agree on the units of analysis in a metric system. Normally however, in traditional seriation techniques, after selecting formal variables for analysis, the archaeologist uses metric data to divide an assemblage (or assemblages) into clusters, classes, or "styles" that reflect a particular period of time. This can be a difficult step and not only does it introduce unwanted subjectivity in an otherwise scientific analysis, but it also discards potentially valuable information inherent in the precision of metric data. By analyzing metric data directly rather than clusters, classes, or styles, OPS can save the archaeologist considerable effort and at the same time prevent information loss and maintain a more objective analysis.

Third, in the interaction of theoretical variables and empirical phenomena, there must be some means of assessing accuracy and correctness (*tolerance limits*). In traditional techniques, archaeologists search for a "perfect" seriation, defined primarily by the concept of unimodality. The preconceived notion of a perfect seriation usually includes the stricture that a class or style will not exhibit a decline in frequency followed by a resurgence (Dunnell 1970). In other words, a class or "style" of artifacts will display a unimodal trajectory (either in presence/absence or in frequency values) over time. In demonstrations, perfect seriations are easily achieved (Dunnell 1970). However in practice, perfectly unimodal seriation results can be elusive. This may be due to problems with data (sampling, measurement errors, etc.), with the complexity of the seriation analysis, or with the nature of formal variation in artifacts over time. Regardless, Cowgill (1972:382) raises the legitimate concern, when a single perfect seriation is not found in traditional seriation techniques, whether "…different workers can agree (with unimportant differences) on the same 'best' sequence." OPS (and *OptiPath* software), on the other hand, relies on an objective algorithm to determine the "best" sequence when a "perfect" one is not possible. Furthermore, objective statistical measures may help archaeologists to determine the relative significance among various seriation results. For the analysis of Rapa Nui statuary in Chapter 3, it is worth noting that multiple seriations are performed to analyze different combinations of statues and seriation criteria variables. This is an analytical approach similar to the one published by LeBlanc (1975). And as LeBlanc suggested, discrepancies reported by the different seriations may indicate that at least one of the variables employed as seriation criteria reflects variability due to a dimension other than time. The practitioner is free to determine objective or arbitrary tolerance limits on the level of agreement between multiple seriations.

A mathematical approach to seriation, like OPS, may find extensive applications in archaeological contexts. The related software eases the analytical burden on archaeologists, making seriations of large, complex datasets both feasible and rapid (the *OptiPath* software implementing the algorithm is freely available for non-commercial purposes at http://www.shepardsons.net/optipath.html). Furthermore, the axiomatic approach (see Appendix A) to the seriation problem makes clear the conditions (assumptions) when use of optimal path seriation is appropriate, and may promote the general applicability of OPS. And finally, OPS offers the ability to combine data from both formal variation and chronometric analyses for a thoroughly-informed chronological analysis. The following chapter presents one real archaeological application of OPS by seriating prehistoric megalithic statuary from Rapa Nui.

CHAPTER 3. SERIATING *MOAI*

Archaeologists have generally agreed that, "The *moai*, although not capable of being directly dated…have real potential for being chronologically ordered (González et al. 1988)" (Van Tilburg 1996:566). Specifically, Van Tilburg (1996:566) suggests that, "statue form, style and iconographic evidence are significantly dependable indicators of time." As is often the case, however, the practice of ordering statues chronologically based on formal variation is far more difficult than the concept appears.

Several archaeological studies or inventories of cultural resources have attempted to thoroughly document megalithic statuary on Rapa Nui. While Routledge, Thomson, and Van Tilburg have all intended to gather a complete inventory of *moai*, their respective counts have varied considerably. Thomson (1891) counted 555 statues on the island; Routledge (1919) suggested a total of 471 statues, not including those statues that had been taken for exhibitions overseas; and in more than thirty years of work in the early 1900's, Father Sebastian Englert may have collected data on more than 800 statues, before his notes were lost (Englert n.d., 1948). The Easter Island Statue Project was initiated in 1982, and under direction of Dr. Jo Anne Van Tilburg, the project has documented somewhere between 886 and 1000 statues (Liller 1993; Van Tilburg 1993). Sadly, nearly twenty-five years after the inception of the Easter Island Statue Project, the accumulated data still has not been made available for the public, for other researchers, or even as archival material for the Padre Sebastián Englert Anthropological Museum on Rapa Nui.

Van Tilburg and her research team have documented statues thoroughly, measuring and categorizing a variety of morphological attributes for each statue, as well as statue locations, postures, orientations, and construction materials. Statistical analyses of the statue data by Van Tilburg and colleagues, in general, have done an excellent job in summarizing statistical trends and abundances for the recorded attributes (González et al. 1988; Van Tilburg 1986, 1993; Vargas 1988). These summaries have also lead to intriguing interpretations of the relationship between statuary and evolving ideological and/or sociopolitical conditions on the island (Van Tilburg 1988).

Beyond simply summarizing group statistics for variability amongst statues, one of Van Tilburg's foremost goals has been to identify a typology for statues that might faithfully reflect formal differences attributable to chronological variation. However, despite innovative data collection techniques and statistical cluster analyses of thirteen morphological attributes meant to identify meaningful statue types, Van Tilburg (1993:89) concludes, "These types have proven to be viable and useful in establishing artefact/context relationship categories within the growing mass of statue data, but are far less helpful in understanding time/areal relationships." Unfortunately, Van Tilburg's attempts to relate statue typologies to phases in *ahu* construction have been unsuccessful (Skjølsvold 1993; Van Tilburg 1986). And in fact, there may be little reason to assume that a cluster or statistical analysis dividing statues into formal types *should* reflect chronology. Such an analytical approach may identify patterns, but offers no theoretical foundation to infer chronology from those patterns.

Overall, detailed analyses of formal variation amongst statues have offered little in terms of an understanding of the changes or progression in statues over time.

Consequently, the evolution of statue form is often described by vague generalizations that do not refer to any quantitative analysis of statuary at all. Skjølsvold (1993:92-94) relays some of the prevailing conceptions of formal variation in statuary over time:

> …the rounded and more naturalistically shaped statues represent the earliest type of *moai* on the island (Skjølsvold/Figueroa 1989:32).

As time continued,

> …there seems to have been a stage of development within the classical style which favored small, broad specimens…

And ultimately,

> …there was a gradual development towards larger and more elegantly shaped specimens. According to this view, the tall, slim, and well-developed statues at the foot of Rano Raraku must belong to the final stage, before the industry ceased.

The objective in this chapter is to apply the optimal path seriation (OPS) approach to analyze formal variability in prehistoric Rapa Nui statuary explicitly so that: (1) we may test or substantiate generalizations such as those made by Skjølsvold; (2) we may develop a more complete understanding of the modes and development of statue form than a simple three-part sequence; and (3) we may derive a chronology for statuary that will allow for both temporal and spatial analyses of energy investment in prehistoric statuary.

Data Collection

Initially, previous studies documenting statue locations and characteristics were considered to provide data for statue seriations. However the earlier survey efforts, including the work of Thomson (1889), Routledge (1919), and Englert (n.d.), lack precise geographic provenience. The later work of Van Tilburg (1986, 1993, 1994) and Riquelme et al. (1991) offer more precise provenience information, but their databases present conflicting information. Liller (1993b:88) commented that, regarding a portion of the database assembled by Van Tilburg and the Easter Island Statue Project, "This impressive compilation of data is, unfortunately, marred by a substantial number of annoying or misleading numerical misprints or errors." Therefore, a new statue survey was conducted not only for this study but to provide a comprehensive database for future research as well. This data is not only available through the Padre Sebastián Englert Anthropological Museum on Rapa Nui, but is also in the process of being published to the World Wide Web by the Hawai'i Biodiversity and Mapping Program.

During approximately ten months of research throughout 2003, 2004, and 2005, information was collected for statues that still remain on Rapa Nui. Although data gathered in this project has already been used for spatial analysis of statuary (Shepardson 2005a, 2005b, 2006a) and for the purposes of archaeological conservation efforts, data was also gathered for the explicit purpose of analyzing formal variability in statues.

An important dimension of the data-collection process and part of the research design as a whole was a non-invasive and non-destructive approach to research-oriented archaeology. This meant that the creation of a large GIS database was somewhat restricted by a policy of minimal physical contact with the statues, and in no cases were statues excavated.

Measurements of twenty-two formal variables on statues were obtained with a tape measure and large calipers (Table 3.1, Figure 3.1). Over all, 15,664 measurements

Table 3.1. List of morphological attributes recorded during fieldwork. A * indicates that the attribute was used as part of a ratio value in seriation analysis.

Morphological Attribute	Cross-Reference Figure 3.1
Total Length*	A
Face Length*	B
Face Width (Eye Level)	C
Face Width (Nose Level)	D
Ear Length (Top)	E
Ear Length (Bottom)	F
Ear Length (Total)	G
Head Width*	H
Head Depth*	I
Forehead Length*	J
Right Eye Width*	K_1
Left Eye Width	K_2
Bridge of Nose (Eye Level)*	L
Nose Width (Maximum)	M
Mouth Width	N
Nose to Mouth*	O
Mouth to Chin*	P
Base Width*	Q
Base Depth*	R

Figure 3.1. Morphological attributes recorded during fieldwork. Letters correspond to Table 3.1.

were recorded for 712 statues. Additionally, data collection included documentation of statues' orientation, posture, stage of completion, and physical condition. Unfortunately, many statues are broken, buried, or eroded to the point where measurements on particular formal variables are either unreliable or virtually impossible. Each statue's location was recorded with a handheld GPS device, and each statue was photographed digitally. In general, a Garmin Etrex Venture handheld GPS unit recorded statues' provenience with a radius of error of less than six meters. However, within the vicinity of the Rano Raraku volcanic crater (the primary statue quarry), significantly less precise geographic information was obtained (a maximum radius of error of twenty-five meters) due to the crater's rim blocking line of sight with some GPS satellites.

Extensive efforts were made to ensure proportionate sampling from all different regions of the island (Shepardson 2005a). Reconnaissance and survey included more than sixty days and hiking more than 500 kilometers. Of all statues recorded, more than 95% were located either through extant documentation (Cristino et al. 1981; Englert n.d.; Riquelme et al. 1991; Routledge 1919; Van Tilburg 1986, 1993) or by local informants and landowners across the island. Satellite imagery provided by Carl Lipo of California State University Long Beach provided a small number of additional statue locations. And finally, the author surveyed several transects across the island which had no prior documentation of statue locations or indications of statues from satellite imagery. These routes, without fail, ended in long days of hiking without any statue encounters.

There are, however, more statues on the island than are represented in the database constructed for this dissertation research fieldwork. While survey efforts for this research identified only 360 statues within the immediate vicinity of the Rano Raraku statue quarry, previous surveys suggest that as many as 396 may actually exist (Van Tilburg 1993). And while survey efforts for this research identified only 352 statues outside of the quarry area, previous field research suggests that as many as 442 statues exist (Van Tilburg 1993). Thus, near the Rano Raraku quarry, this one-man survey effort appears to have identified nearly 91% of known statues. Outside of the quarry area, 80% of known statues were identified. There is one obvious subgroup of statues *outside* of the quarry area that were underrepresented by field research for this dissertation.

Statues that have been re-erected in the last three decades were placed in the GIS database but were not measured. These statues were excluded in fieldwork so that ladders/scaffolding and contact with reconstructed (and heavily touristed) areas were not necessary. In order to include some of these statues in the analysis, data acquired previously by Riquelme et al. (1991) was incorporated for thirty-one statues. Those statues for which Riquelme et al.'s data were used are marked by an (R) in following tables.

Applying Optimal Path Seriation

Optimal Path Seriation has successfully seriated data sets using anywhere between three and six formal variables to describe the artifacts. Based on this success, six ratios are initially selected as the formal variables in the task of seriating the prehistoric statues of Rapa Nui: *WL* (width of statue base: total length of statue), *BB* (depth of statue base: width of statue base), *HH* (depth of statue head: width of statue head), *NC* (distance from nose to mouth: distance from mouth to chin), *EB* (width of right eye: width of bridge of the nose), *FF* (length of forehead: length of face). Ratios are used in all cases to ensure independence between formal variability and overall statue size. These particular variables were selected as examples of highly visible and aesthetically impactful formal dimensions that are relatively easy to identify and measure.

Measures for each variable are drawn from the recently compiled database of 712 statues. However, given the natural weathering of statues, long-term erosion, and the orientation in which statues now reside (face down, erected, partially buried, etc.), it was not possible to collect data for all six variables for all statues. In fact, only fourteen statues have data for all six variables. This small number presents little potential for a representative sample and serious problems for developing a broad chronology for statue construction events.

Therefore, statues are selected for seriation analysis based on the criteria that each statue offers data for at least three out of the six variables, yielding 203 statues for seriation analysis. The larger sample size, in turn, increases the chances of a meaningful and complete chronology but also adds a degree of statistical complexity to the analysis. Since statues do not necessarily have measurements for the same variables, determining stylistic continuity from one statue to the next may be impossible. Therefore, the statues cannot all be included in a single, meaningful seriation. To ensure that all statues appear in at least one seriation, the analysis offers seriations for all twenty possible combinations of three variables from our six initial variables. The analysis then presents several variations on parameters for statue seriations for comparison.

The seriation analysis also offers seriations for all fifteen possible combinations of four variables from our six initial variables. Finally, for three-variable seriations and four-variable seriations, all statues that currently reside in the Rano Raraku quarry area are removed from the analysis, and the seriations are recalculated. Quarry statues are initially included in the analysis as they may play a critical role in ensuring the seriation results offer a representative sample of stylistic change. However, the argument can also be made that there is little reason to believe that statues that are still in the quarry had actually reached a final, complete state. Therefore, any analysis of their formal variability would be premature.

The process of comparing multiple seriation results becomes complex and cumbersome, but may actually offer some rigor and confidence to the conclusions. At each stage of the analysis, seriation results are compared to prior results. And ultimately, a number of orderings are considered as chronological and worthy of further consideration or analysis.

To ensure that statue orderings are consistent with existing data for the chronology of ceremonial site construction on the island, the OPS seriation algorithm and *OptiPath* software allow for the inclusion of specific dates or date ranges to constrain seriation results. If we assume that the *ahu* (or at least a particular phase of *ahu* construction) upon which statues stood was completed prior to erection of those statues, we may constrain our seriation results by a number of radiocarbon and obsidian hydration dates published for various *ahu*. However, it is possible that in some cases statues were constructed before the construction (or remodeling) of *ahu*. Table 3.2 lists a series of relevant published *ahu* construction dates, and the corresponding date applied as a constraint in seriation analysis. The construction date for each *ahu* is not used as an exact date for statue construction but rather a conservative lower (early) bound. The upper bound for all statue construction events is assumed to be AD 1700.

The terminal date for statue construction around AD 1700 has been suggested on several occasions prior to this research (e.g., Ayers 1975; Mulloy and Figueroa 1978; Skjølsvold 1993; Smith 1962). The accuracy of this date remains to be determined, but the date seems to offer a reasonable mid-range estimate, given the different observations made by early visitors to the island. Geiseler's 1882 report from the island (published in 1995), concluded that statue construction had ceased as early 1630. However, all statues on *ahu* apparently still stood erect at the time of Roggeveen's 1722 and González de Haedo's 1770 visits to the island (Fischer 2005). And while statue construction may have ceased sometime around AD 1700, construction or remodeling of other forms of monuments (especially *avanga* and semi-pyramidal *ahu*) almost certainly continued for some time afterward (Love 1993; Smith 1962).

The possibility that statues were constructed before AD 1000 or after AD 1700 cannot be ignored. In the case that evidence suggesting a significantly different range of dates for statue construction emerges, a re-analysis can be performed relatively expediently using the *OptiPath* software. However, it should also be noted that simply expanding, compressing, or shifting the range of dates for statue construction is not likely to alter the *relative* ordering of statues that results from seriation analysis in this chapter. Furthermore, the AD 1700 date precedes European contact with the island by only a couple decades. It is beyond the scope of this work to try to explain or understand post-contact conditions on the island.

Table 3.2. Bounding dates applied to OPS analysis.

Statue Ref.	*Ahu* Name	Published Chronometric Information	Type	Reference	Early Bounding Date Applied to Seriation Analysis
02-209	Vinapu 2	1310-1496 1250-1430	c c	1 2	1250
02-210	Vinapu 1	1028-1428 1350-1550 1082-1419	c c c	3 4 1	1028
05-297	Huri A Urenga	1082-1258 c1200	c c	5 6	1082
06-191	Tarakiu	1371-1493	o	7	1371
06-255	Hanga Te'e	1301-1429	o	7	1301
07-575	Ura Uranga Te Mahina	1346-1470	o	7	1346
07-581		1527-1629	o	7	1527
07-584	Akahanga	1423-1579	o	7	1423
08-001	Ko Te Riku	1010-1305 1072-1231 969-1155 1158-1321 1051-1218 1110-1205	c c c b c c	4 4 4 4 8 6	1000
08-002	Tahai II	1130-1290 1126-1272	c b	4 8	1126
08-003	Vai Uri	c1200	c	9	1100
12-447	Hoa Anga Vaka o Tua Poi	1517-1623	o	7	1517
12-460 12-460-01	Oroi Oroi	1383-1505 1554-1656	o o	7 7	1383 1554
Akivi	Akivi	1440-1621 1485-1752 1311-1445 1427-1592	c b,c b,c c	6 6 6 6	1311
Ature Huki	Ature Huki	1350-1513 1314-1429	c c	1 1	1314
Heki'i	Heki'i	1300-1400	c	10	1300
Nau Nau	Nau Nau	1051-1265 1269-1374 1188-1378 1305-1412	c c c c	1 1 1 1	1051
Tepeu	Tepeu	1481-1823	b	11	1481
14-548	Tongariki	post-1300	s	12	1300

Type
b bone
c charcoal
o obsidian
s speculative

Reference
1 Reports in Kon-Tiki Musem Archive
2 Skjølsvold 1993
3 Mulloy 1961
4 Ayres 1971
5 Esen-Baur 1983
6 Mulloy and Figueroa 1978
7 Stevenson 1984
8 Ayres 1973
9 Martinsson-Wallin 1994
10 Martinsson-Wallin and Wallin 2000
11 Heyerdahl and Ferdon 1961
12 Stevenson 2002

If, on the other hand, novel chronometric information emerges for one of the ceremonial sites listed in Table 3.2 (acting as one of the "anchor" dates), seriation results could change. These changes must be considered on a case-by-case basis as they arise in the future.

Seriating with Three Formal Variables (Analysis #1)

Results of three-variable seriations are displayed in Table 3.3. Rather than being simply ordered, each statue has been assigned a date using the OPS algorithm. These dates are assigned based on the assumption that all statues were constructed between AD 1000 and 1700 and that the rate of stylistic change during that period was relatively steady. Based on the twenty possible combinations of three features, each statue can appear in up to twenty seriations—a statue providing data for all six variables appears in all twenty seriations; a statue providing data for five variables appears in ten seriations; a statue providing data for four variables appears in four seriations; and a statue providing data for three variables appears in only one seriation.

An average date is calculated for each statue as a general result and the standard deviation is displayed as a measure of confidence for statues appearing in more than one seriation. A large standard deviation indicates little agreement from one seriation to the next, and in turn, little confidence in the results. Statues that appear in few or only one

Table 3.3. Three-variable optimal path seriation results (Analysis #1).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
02-209-02								1680													1680	
02-209-03				1098																	1098	
02-209-04	1303	1123	1344	1171	1091	1068	1325	1129	1401	1217	1282	1111	1093	1091	1607	1281	1613	1134	1068	1048	1225	168.88
02-210-02		1284																			1284	
02-210-06	1330			1110			1314						1052								1201.5	141.29
02-228-01								1491	1000	1700										1700	1472.75	330.21
03-077-01	1093	1566	1118	1626	1526	1372	1538	1284	1498	1441	1508	1409	1509	1156	1510	1542	1130	1292	1287	1125	1376.5	176.25
05-080-01	1186	1042	1517	1657	1415	1177	1628	1700	1700	1614	1373	1700	1608	1665	1344	1037	1000	1000	1666	1462	1424.55	261.89
05-197-01(R)		1421																			1421	
06-191-01				1293																	1293	
06-255-05				1154																	1154	
07-200-01				1437																	1437	
07-575-04				1179																	1179	
07-581-01		1161	1236	1308				1414	1252	1296				1039	1063	1359				1249	1237.7	120.35
07-584-01								1404	1228	1263										1192	1271.75	92.81
07-584-02		1445		1127					1352						1140						1266	157.73
07-584-03		1492	1140	1485				1434	1263	1234				1256	1096	1256				1269	1292.5	135.92
07-584-09		1082		1298					1160						1576						1279	217.21
07-584-14																1153					1153	
08-001-01(R)		1146																			1146	
08-002-01(R)		1383																			1383	
08-003-02(R)		1700	1667					1000						1618							1496.25	332.54
08-003-05(R)		1340																			1340	
08-345-01	1519	1329	1429	1095	1612	1495	1217	1156	1440	1505	1529	1336	1536	1328	1478	1129	1054	1373	1223	1561	1367.2	170.57
10-020-01							1413														1413	
11-205-01				1406																	1406	
12-076-01	1286			1233			1305						1118								1235.5	84.05
12-220-01		1321	1419	1117				1145	1413	1211				1322	1161	1188				1033	1233	129.77
12-323-01			1224	1330						1308						1372					1308.5	62.28
12-397-01		1051																			1051	
12-447-01			1563	1560						1487						1165					1443.75	189.13
12-452-01				1646																	1646	
12-460-01		1207		1338					1203						1043						1197.75	120.73
12-460-03		1503	1157	1465				1421	1238	1269				1276	1123	1236				1230	1291.8	128.48
12-460-04		1511	1166	1461				1226	1221	1277				1298	1115	1290				1239	1280.4	122.41
13-052-01	1156		1148			1433						1383									1280	149.24
13-096-01	1174		1193			1392						1379									1284.5	117.00
13-331-01		1315		1515					1429						1488						1436.75	88.76
13-332-01	1592																				1592	
13-403-01										1169											1169	
13-477-01	1223			1318			1450						1201								1298	113.34
13-478-01	1560		1365	1502		1561	1358			1116		1176	1246			1427			1366		1367.7	153.08
13-481-01	1506			1084			1197						1541								1332	226.34
13-485-01	1100			1572			1518						1526								1429	220.62
13-486-01	1193			1426			1571						1221								1352.75	178.77
13-487-01	1586		1175	1476		1245	1428			1283		1147	1082			1299			1055		1277.6	174.49
13-488-01	1235			1279			1268						1143								1231.25	61.73
13-490-01			1208	1418						1453						1416					1373.75	111.80
13-492-01										1448											1448	
13-593-01	1553			1162			1284						1133								1283	191.52
14-021-01		1024		1148					1141						1659						1243	283.11
14-021-02	1240			1286			1259						1153								1234.5	57.52

Table 3.3. (Continued) Analysis #1.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
14-021-03		1230		1256					1365						1000						1212.75	153.42
14-159-01			1311	1218						1496						1342					1341.75	115.55
14-160-01							1506														1506	
14-463-02	1049	1588	1553	1568	1159	1225	1457	1181	1475	1481	1556	1318	1557	1340	1470	1139	1037	1249	1166	1554	1356.1	190.44
14-493-02				1358																	1358	
14-548-01(R)	1534	1344	1379		1647	1541		1464			1609	1209		1194			1228				1414.9	168.81
14-548-02(R)	1482		1442			1610						1307									1460.25	124.79
14-548-03(R)	1123	1302	1333		1574	1472		1570			1469	1361		1294			1157				1365.5	156.29
14-548-04(R)		1351																			1351	
14-548-06(R)	1339	1636	1400		1053	1056		1096			1162	1280		1536			1640				1319.8	229.35
14-548-07(R)	1544	1297	1341		1657	1577		1561			1663	1163		1286			1450				1453.9	173.18
14-548-08(R)	1529	1463	1385		1674	1535		1537			1631	1200		1229			1370				1455.3	158.40
14-548-09(R)																	1236				1236	
14-548-11(R)																	1424				1424	
14-548-12(R)																	1391				1391	
14-548-17	1599	1506	1131	1470	1277	1275	1438	1396	1244	1255	1657	1184	1072	1245	1108	1248	1465	1431	1127	1201	1316.45	168.28
14-548-18												1519									1519	
14-548-19																			1191		1191	
14-548-20																	1684	1660	1607	1451	1600.5	104.73
18-303-01	1264			1384			1675						1645								1492	200.45
18-350-01				1324																	1324	
Akivi-01(R)		1404	1029					1453						1477							1340.75	210.04
Akivi-02(R)		1437																			1437	
Akivi-03(R)		1456																			1456	
Akivi-04(R)		1450																			1450	
Akivi-05(R)		1475																			1475	
Akivi-06(R)		1418																			1418	
Akivi-07(R)		1431																			1431	
Ature Huki-01(R)		1677																			1677	
L-01											1068	1566	1381	1580	1413	1663	1660	1191	1564	1528	1461.4	199.09
Mahina-01	1580																				1580	
Mahina-02	1324																				1324	
Mata Ketu-01		1000	1472	1061				1067	1079	1518				1700	1700	1113				1506	1321.6	282.86
MTM-01			1700	1000						1038						1093					1207.75	330.38
Museo-01(R)																	1532				1532	
Museo-07																	1554	1504	1544	1578	1545	30.83
Nau Nau-01-01(R)		1312	1490					1636						1367							1451.25	143.90
Nau Nau-01-02(R)		1394	1581					1586						1438							1499.75	98.38
Nau Nau-01-03(R)		1242	1288					1626						1000							1289	257.75
Nau Nau-01-04(R)		1387	1604					1609						1411							1502.75	120.22
Nau Nau-01-05(R)		1469																			1469	
Nau Nau-01-10	1623	1543	1539	1670	1322	1125	1700	1201	1532	1630	1241	1641	1322	1374	1299	1062	1576	1631	1620	1426	1453.85	196.55
New Ahu-01			1456	1048						1071						1450					1256.25	227.39
New Ahu-03	1563	1118		1496	1131		1366		1456		1338		1239		1539			1239			1348.5	163.45
Paro(R)	1078																				1078	
Piti-01	1574			1490			1381						1257								1425.5	137.34
Poike-06	1494																				1494	
Road-I-03	1229			1312			1462						1203								1301.5	116.66
Road-I-06	1141	1095		1226	1476		1240		1123		1401		1169		1588			1065			1252.4	176.87
Road-N-Ahu-01	1248			1303			1474						1187								1303	123.45
Road-NW-05		1104	1354	1184				1113	1113	1136				1109	1556	1267				1066	1200.2	152.71
Road-NW-06								1646	1410	1544										1000	1400	283.64

Table 3.3. (Continued) Analysis #1.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
Road-NW-10			1077	1599						1350						1555					1395.25	238.30
RR-020																	1067	1274	1205	1541	1271.75	199.06
RR-033														1473	1187	1611				1196	1366.75	210.09
RR-034																	1248	1097	1107	1180	1158	70.49
RR-035						1202	1578			1573									1175		1382	223.72
RR-037																		1700			1700	
RR-043																	1270	1263	1388	1116	1259.25	111.40
RR-053									1650												1650	
RR-054																	1291				1291	
RR-056										1094											1094	
RR-058																	1220	1324	1310	1144	1249.5	84.09
RR-062																	1482	1548	1440	1301	1442.75	104.43
RR-064								1332	1633	1367										1117	1362.25	211.65
RR-066						1414	1548			1467									1212		1410.25	143.19
RR-070								1248	1596	1332										1254	1357.5	163.54
RR-072																	1630	1151	1077	1063	1230.25	269.28
RR-082																	1242	1394	1374	1133	1285.75	122.14
RR-084																	1310	1175	1344	1641	1367.5	196.40
RR-087																				1566	1566	
RR-091	1000		1000	1700		1448	1649			1653		1465	1432			1700			1700		1474.7	272.39
RR-092								1137	1419	1223										1040	1204.75	161.21
RR-096																				1400	1400	
RR-097																	1290	1209	1436	1105	1260	139.64
RR-099																	1322				1322	
RR-112								1270	1207	1319										1597	1348.25	172.05
RR-114			1065	1583						1314						1574					1384	246.55
RR-126																	1195	1362	1237	1591	1346.25	177.92
RR-129	1613	1576	1111	1620	1363	1296	1398	1317	1486	1385	1202	1251	1276	1142	1525	1530	1299	1170	1354	1632	1377.3	165.37
RR-132		1058		1449					1181						1598						1321.5	246.23
RR-149	1294	1133	1319	1159	1100	1088	1298	1164	1390	1178	1302	1132	1108	1070	1625	1316	1598	1121	1041	1022	1222.9	169.33
RR-226																	1382	1445	1093	1221	1285.25	159.13
RR-227														1271							1271	
RR-238																			1149		1149	
RR-241																	1201	1308	1297	1375	1295.25	71.67
RR-242																	1458	1421	1136	1260	1318.75	149.10
RR-251	1425																				1425	
RR-254				1104																	1104	
RR-257																				1341	1341	
RR-258	1071	1553	1105	1640	1180	1336	1610	1344	1514	1424	1587	1219	1588	1177	1277	1484	1257	1593	1405	1676	1402	191.72
RR-259									1215												1215	
RR-261																				1162	1162	
RR-262																	1327	1227	1331	1649	1383.5	183.42
RR-265																				1571	1571	
RR-267								1366	1575	1363										1350	1413.5	107.89
RR-269																			1266		1266	
RR-271																				1275	1275	
RR-273	1311			1511			1341						1267								1357.5	106.75
RR-277(R)																	1111				1111	
RR-A-001								1552	1335	1159										1235	1320.25	170.48
RR-A-006		1599	1042	1557				1303	1465	1242				1505	1456	1594				1624	1438.7	187.97
RR-A-010									1673												1673	
RR-A-011																				1318	1318	

Table 3.3. (Continued) Analysis #1.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
RR-A-017										1401											1401	
RR-A-018																	1352	1574	1394	1306	1406.5	117.31
RR-A-019																	1255	1383	1312	1657	1401.75	178.04
RR-A-021																				1121	1121	
RR-A-022																				1282	1282	
RR-A-027	1068	1517	1109	1631	1262	1330	1597	1387	1568	1435	1616	1214	1576	1200	1253	1498	1359	1571	1383	1360	1396.7	173.26
RR-A-038	1207	1182			1239						1690										1329.5	241.46
RR-A-044/RR-A-045																			1472		1472	
RR-A-047																				1670	1670	
RR-A-048																	1283	1219	1444	1112	1264.5	138.91
RR-A-062																				1336	1336	
RR-A-071																				1333	1333	
RR-A-072																	1491	1477	1337	1290	1398.75	100.45
RR-A-075/RR-A-076														1210	1226	1520				1291	1311.75	143.18
RR-A-078																	1486	1543	1450	1299	1444.5	104.28
RR-A-079																	1513	1531	1459	1364	1466.75	75.02
RR-A-080																				1608	1608	
RR-A-088																	1346	1403	1323	1149	1305.25	109.46
RR-A-089	1062	1560	1098	1614	1189	1321	1585	1340	1623	1378	1572	1229	1566	1168	1502	1511	1262	1389	1318	1655	1397.1	187.69
RR-A-093																				1370	1370	
RR-A-099																	1340	1606	1416	1683	1511.25	160.08
RR-A-100		1527		1609					1581						1241						1489.5	169.13
RR-A-104																	1503	1540	1463	1355	1465.25	79.94
RR-A-105		1366		1076					1305						1209						1239	126.43
RR-A-109	1448	1264		1199	1700		1181		1293		1700		1207		1074			1413			1347.9	215.29
RR-B-09	1700		1253	1365		1011	1057			1108		1000	1700			1390			1519		1310.3	268.92
RR-B-12	1394		1638	1022		1665	1139			1000		1667	1305			1016			1642		1348.8	290.22
RR-C-01																				1365	1365	
RR-C-06																	1179	1346	1250	1265	1260	68.51
RR-C-09																				1616	1616	
RR-C-10																				1092	1092	
RR-C-17																			1493		1493	
RR-C-34								1375	1556	1416										1325	1418	99.24
RR-C-37																				1661	1661	
RR-D-07																	1477	1556	1431	1346	1452.5	87.78
RR-D-14																		1465			1465	
RR-D-24																				1312	1312	
RR-D-30								1525	1321	1147										1216	1302.25	164.83
RR-D-32																				1206	1206	
RR-D-39																				1383	1383	
RR-D-42																				1668	1668	
RR-D-47					1210	1346	1564	1354	1615	1374							1213	1317	1307	1138	1343.8	150.00
S-001-01	1367	1656	1626	1032	1000	1700	1106	1036	1048	1010	1126	1614	1348	1630	1381	1000	1700	1678	1593	1478	1356.45	281.69
Solo-O1	1467																				1467	
Tepeu-02	1015	1619	1016	1543	1462	1512	1223	1104	1103	1127	1000	1449	1476	1559	1431	1637	1086	1047	1232	1075	1285.8	230.44
Tepeu-04	1656		1415	1135		1000	1000			1192		1061	1000			1212			1000		1167.1	217.84
Terevaka-01	1038			1525			1489						1548								1400	242.55

Columns 1-20 refer to seriations containing the following formal variables: 1 - WL,BB,HH; 2 - WL,BB,NC; 3 - WL,BB,EB; 4 - WL,BB,FF; 5 - WL,HH,NC; 6 - WL,HH,EB; 7 - WL,HH,FF; 8 - WL,NC,EB; 9 - WL,NC,FF; 10 - WL,EB,FF; 11 - BB,HH,NC; 12 - BB,HH,EB; 13 - BB,HH,FF; 14 - BB,NC,EB; 15 - BB,NC,FF; 16 - BB,EB,FF; 17 - HH,NC,EB; 18 - HH,NC,FF; 19 - HH,EB,FF; 20 - NC,EB,FF.

seriation may provide little in terms of a meaningful standard deviation. However, there appears to be almost no correlation between the standard deviation and the number of seriations in which a statue appears ($R^2 = 0.05$). This may suggest that the number of seriations in which a statue appears should not directly affect confidence in the results. As a point of comparison for subsequent seriations, the three-variable seriations display an average standard deviation for each statue of 166.5 years.

Seriating with Three Formal Variables and Chronometric Constraints (Analysis #2)

In an effort to reduce the variation in results for statues and to prevent conflict between statue dates and known *ahu* construction dates, early bounding dates are applied to forty-nine statues, and the three-variable seriations are recalculated. Results are displayed in Table 3.4. Chronometric information for forty-nine (out of 203) statues may seem to be a major improvement, but in many cases the conservative dates for *ahu* construction do not narrow down our possible time frame for statue construction significantly. For example, statue 05-297-01 at *ahu* Huri A Urenga, with chronometric constraints must appear between AD 1082 and 1700 in seriation results (as opposed to AD 1000 and 1700). Similarly, when conservative construction dates for *ahu* Ko Te Riku are applied to statue 08-001-01, no additional information is gained.

Recalculation including chronometric constraints again produces twenty separate seriations. The average standard deviation for each statue's calculated average date is

Table 3.4. Three-variable optimal path seriation results applying chronometric constraints from Table 3.1 (Analysis #2).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
02-209-02								1250													1250	
02-209-03				1386																	1386	
02-209-04	1286	1594	1361	1432	1612	1634	1383	1578	1324	1483	1496	1256	1269	1268	1550	1624	1319	1566	1633	1532	1460	139.28
02-210-02		1088																			1088	
02-210-06	1320			1517			1394						1649								1470	144.37
02-228-01								1413	1006	1000										1361	1195	222.73
03-077-01	1436	1232	1441	1095	1292	1375	1176	1087	1265	1273	1264	1442	1568	1198	1189	1396	1500	1408	1453	1401	1324.55	136.08
05-080-01	1172	1186	1095	1064	1000	1186	1020	1231	1088	1084	1041	1175	1091	1370	1401	1109	1000	1700	1034	1169	1160.8	167.52
05-197-01(R)		1399																			1399	
06-191-01				1669																	1669	
06-255-05				1480																	1480	
07-200-01				1616																	1616	
07-575-04				1439																	1439	
07-581-01		1539	1689	1656				1535	1527	1589				1670	1628	1671				1637	1614.1	61.97
07-584-01								1501	1492	1445										1562	1500	48.08
07-584-02		1423		1503					1460						1700						1521.5	123.41
07-584-03		1463	1659	1423				1474	1516	1428				1614	1659	1646				1621	1550.3	98.67
07-584-09		1574		1664					1596						1580						1603.5	41.39
07-584-14																1511					1511	
08-001-01(R)		1070																			1070	
08-002-01(R)		1359																			1359	
08-003-02(R)		1700	1211					1700						1419							1507.5	237.95
08-003-05(R)		1321																			1321	
08-345-01	1366	1280	1307	1383	1483	1509	1489	1147	1375	1662	1243	1542	1595	1170	1204	1543	1561	1327	1531	1073	1389.5	167.36
10-020-01							1298														1298	
11-205-01				1182																	1182	
12-076-01	1270			1466			1402						1246								1346	105.38
12-220-01		1272	1600	1511				1566	1349	1477				1176	1229	1562				1668	1441	171.74
12-323-01			1700	1637						1403						1683					1605.75	137.76
12-397-01		1195																			1195	
12-447-01			1575	1552						1645						1522					1573.5	52.37
12-452-01				1075																	1075	
12-460-01		1554		1631					1557						1609						1587.75	38.33
12-460-03		1473	1422	1590				1486	1502	1450				1630	1684	1607				1587	1543.1	87.44
12-460-04		1480	1394	1587				1527	1540	1459				1643	1677	1616				1577	1550	87.80
13-052-01	1417		1666			1434						1392									1477.25	127.01
13-096-01	1160		1407			1394						1396									1339.25	119.64
13-331-01		1290		1394					1365						1213						1315.5	81.18
13-332-01	1061																				1061	
13-403-01										1525											1525	
13-477-01	1208			1648			1261						1164								1320.25	222.07
13-478-01	1048		1652	1407		1614	1351			1240		1356	1310			1288			1331		1359.7	173.96
13-481-01	1547			1372			1508						1599								1506.5	97.11
13-485-01	1442			1572			1195						1585								1448.5	180.91
13-486-01	1179			1162			1144						1144								1157.25	16.80
13-487-01	1075		1385	1596		1252	1283			1464		1240	1280			1206			1645		1342.6	179.09
13-488-01	1220			1681			1439						1221								1390.25	219.50
13-490-01			1676	1170						1261						1277					1346	224.99
13-492-01										1266											1266	
13-593-01	1041			1474			1424						1231								1292.5	197.71
14-021-01		1168		1485					1614						1076						1335.75	255.15
14-021-02	1225			1675			1448						1211								1389.75	218.98

Table 3.4. (Continued) Analysis #2.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
14-021-03		1040		1700					1472						1000						1303	340.17
14-159-01			1034	1453						1653						1246					1346.5	266.48
14-160-01							1207														1207	
14-463-02	1468	1615	1584	1569	1041	1232	1255	1171	1288	1639	1193	1560	1624	1157	1519	1533	1034	1451	1518	1080	1376.55	213.36
14-493-02				1222																	1222	
14-548-01(R)	1351	1317	1638		1450	1595		1388			1371	1324		1597			1447				1447.8	120.83
14-548-02(R)	1578		1319			1540						1570									1501.75	122.93
14-548-03(R)	1385	1302	1371		1339	1471		1551			1300	1414		1646			1583				1436.2	121.71
14-548-04(R)		1327																			1327	
14-548-06(R)	1312	1651	1618		1649	1646		1609			1594	1596		1499			1340				1551.4	126.80
14-548-07(R)	1342	1308	1364		1440	1571		1366			1391	1369		1637			1676				1446.4	132.07
14-548-08(R)	1356	1438	1632		1388	1589		1458			1351	1333		1570			1623				1473.8	119.02
14-548-09(R)																	1439				1439	
14-548-11(R)																	1700				1700	
14-548-12(R)																	1642				1642	
14-548-17	1067	1476	1429	1583	1161	1281	1273	1494	1534	1437	1386	1348	1291	1606	1670	1638	1666	1269	1574	1614	1439.85	175.55
14-548-18												1000									1000	
14-548-19																			1493		1493	
14-548-20																	1239	1040	1092	1179	1137.5	88.70
18-303-01	1247			1204			1086						1054								1147.75	92.41
18-350-01				1642																	1642	
Akivi-01(R)		1381	1524					1378						1545							1457	89.91
Akivi-02(R)		1415																			1415	
Akivi-03(R)		1432																			1432	
Akivi-04(R)		1427																			1427	
Akivi-05(R)		1449																			1449	
Akivi-06(R)		1396																			1396	
Akivi-07(R)		1408																			1408	
Ature Huki-01(R)		1683																			1683	
L-01											1636	1046	1443	1459	1466	1035	1284	1509	1135	1105	1311.8	218.26
Mahina-01	1081																				1081	
Mahina-02	1326																				1326	
Mata Ketu-01		1143	1147	1349				1637	1672	1675				1333	1115	1180				1126	1337.7	237.77
MTM-01			1180	1288						1173						1162					1200.75	58.64
Museo-01(R)																	1169				1169	
Museo-07																	1190	1196	1155	1060	1150.25	62.82
Nau Nau-01-01(R)		1293	1130					1291						1051							1191.25	120.73
Nau Nau-01-02(R)		1371	1292					1339						1126							1282	108.94
Nau Nau-01-03(R)		1051	1055					1301						1700							1276.75	305.43
Nau Nau-01-04(R)		1364	1270					1317						1097							1262	116.50
Nau Nau-01-05(R)		1444																			1444	
Nau Nau-01-10	1105	1255	1116	1051	1117	1136	1061	1190	1051	1069	1139	1118	1384	1058	1359	1133	1210	1069	1079	1204	1145.2	96.56
New Ahu-01			1332	1336						1205						1310					1295.75	61.57
New Ahu-03	1051	1598		1412	1573		1343		1307		1074		1303		1162			1461			1328.4	190.83
Paro(R)	1147																				1147	
Piti-01	1087			1418			1328						1321								1288.5	141.41
Poike-06	1535																				1535	
Road-I-03	1214			1652			1250						1162								1319.5	224.59
Road-I-06	1402	1583		1460	1519		1466		1630		1015		1195		1568			1635			1447.3	199.95
Road-N-Ahu-01	1232			1660			1238						1178								1327	223.63
Road-NW-05		1117	1352	1444				1593	1640	1557				1287	1146	1656				1515	1430.7	197.33
Road-NW-06								1282	1346	1700										1700	1507	224.38

Table 3.4. (Continued) Analysis #2.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
Road-NW-10			1480	1117						1362						1408					1341.75	157.51
RR-020																	1548	1426	1479	1093	1386.5	201.94
RR-033														1548	1254	1461				1566	1457.25	143.05
RR-034																	1429	1603	1594	1551	1544.25	80.11
RR-035						1210	1137			1626									1508		1370.25	234.14
RR-037																		1000			1000	
RR-043																	1417	1437	1310	1469	1408.25	68.91
RR-053									1137												1137	
RR-054																	1372				1372	
RR-056										1227											1227	
RR-058																	1458	1376	1387	1018	1309.75	197.87
RR-062																	1123	1152	1258	1315	1212	89.90
RR-064								1073	1154	1345										1470	1260.5	180.30
RR-066						1415	1166			1604									1471		1414	183.35
RR-070								1001	1190	1379										1632	1300.5	269.55
RR-072																	1349	1549	1624	1518	1510	116.19
RR-082																	1434	1306	1323	1028	1272.75	172.76
RR-084																	1386	1525	1354	1459	1431	76.54
RR-087																				1068	1068	
RR-091	1499		1552	1023		1447	1000			1046		1496	1493			1000			1000		1255.6	256.45
RR-092								1132	1355	1577										1661	1431.25	237.62
RR-096																				1229	1229	
RR-097																	1374	1491	1262	1477	1401	106.34
RR-099																	1397				1397	
RR-112								1513	1552	1392										1650	1526.75	106.73
RR-114			1491	1133						1398						1426					1362	157.56
RR-126																	1482	1338	1432	1645	1474.25	128.54
RR-129	1114	1222	1447	1145	1077	1301	1312	1099	1278	1328	1102	1284	1339	1239	1175	1384	1365	1530	1344	1451	1276.8	129.03
RR-132		1202		1607					1577						1559						1486.25	190.53
RR-149	1277	1100	1026	1472	1603	1100	1410	1155	1335	1516	1477	1225	1256	1018	1044	1221	1305	1579	1659	1679	1322.85	216.20
RR-226																	1651	1255	1608	1596	1527.5	183.19
RR-227														1626							1626	
RR-238																			1552		1552	
RR-241																	1476	1392	1444	1034	1336.5	204.62
RR-242																	1659	1279	1565	1626	1532.25	173.27
RR-251	1000																				1000	
RR-254				1523																	1523	
RR-257																				1254	1254	
RR-258	1140	1245	1453	1081	1254	1339	1105	1062	1250	1290	1223	1314	1109	1220	1338	1341	1080	1107	1293	1384	1231.4	115.09
RR-259									1546												1546	
RR-261																				1000	1000	
RR-262																	1402	1473	1366	1419	1415	44.53
RR-265																				1053	1053	
RR-267								1020	1211	1350										1263	1211	139.65
RR-269																			1404		1404	
RR-271																				1290	1290	
RR-273	1294			1397			1367						1331								1347.25	44.59
RR-277(R)																	1065				1065	
RR-A-001								1357	1442	1534										1582	1478.75	99.81
RR-A-006		1624	1512	1550				1112	1298	1420				1523	1506	1444				1442	1443.1	145.47
RR-A-010									1114												1114	
RR-A-011																				1339	1339	

Table 3.4. (Continued) Analysis #2.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
RR-A-017										1312											1312	
RR-A-018																	1105	1126	1304	1320	1213.75	113.96
RR-A-019																	1077	1317	1385	1412	1297.75	152.50
RR-A-021																				1397	1397	
RR-A-022																				1297	1297	
RR-A-027	1137	1486	1449	1090	1175	1334	1118	1040	1219	1279	1364	1320	1121	1593	1316	1355	1452	1129	1315	1264	1277.8	148.97
RR-A-038	1192	1520			1197						1416										1331.25	163.53
RR-A-044/RR-A-045																			1226		1226	
RR-A-047																				1390	1390	
RR-A-048																	1406	1481	1254	1466	1401.75	103.69
RR-A-062																				1250	1250	
RR-A-071																				1247	1247	
RR-A-072																	1131	1223	1360	1304	1254.5	99.71
RR-A-075/RR-A-076														1585	1290	1376				1306	1389.25	135.74
RR-A-078																	1127	1157	1248	1313	1211.25	85.14
RR-A-079																	1152	1169	1240	1268	1207.25	55.61
RR-A-080																				1427	1427	
RR-A-088																	1099	1297	1374	1012	1195.5	168.47
RR-A-089	1131	1238	1460	1102	1245	1325	1129	1065	1164	1334	1209	1305	1616	1211	1197	1366	1084	1311	1379	1414	1264.25	140.76
RR-A-093																				1273	1273	
RR-A-099																	1093	1094	1282	1377	1211.5	141.67
RR-A-100		1494		1106					1205						1305						1277.5	165.63
RR-A-104																	1143	1160	1236	1279	1204.5	64.04
RR-A-105		1342		1365					1413						1274						1348.5	57.81
RR-A-109	1022	1010		1253	1412		1523		1401		1426		1158		1639			1287			1313.1	206.96
RR-B-09	1700		1000	1230		1689	1644			1248		1700	1000			1700			1179		1409	304.25
RR-B-12	1594		1239	1309		1000	1565			1135		1143	1368			1090			1058		1250.1	206.75
RR-C-01																				1269	1269	
RR-C-06																	1603	1354	1420	1618	1498.75	131.96
RR-C-09																				1435	1435	
RR-C-10																				1490	1490	
RR-C-17																			1206		1206	
RR-C-34								1029	1230	1297										1332	1222	135.45
RR-C-37																				1408	1408	
RR-D-07																	1118	1144	1267	1259	1197	77.02
RR-D-14																		1235			1235	
RR-D-24																				1326	1326	
RR-D-30								1446	1429	1546										1600	1505.25	81.57
RR-D-32																				1609	1609	
RR-D-39																				1041	1041	
RR-D-42																				1391	1391	
RR-D-47					1225	1350	1151	1052	1172	1338							1465	1383	1390	1024	1255	151.95
S-001-01	1620	1667	1250	1320	1700	1034	1597	1666	1700	1145	1560	1092	1410	1407	1436	1074	1254	1022	1106	1154	1360.7	245.55
Solo-O1	1563																				1563	
Tepeu-02	1514	1639	1536	1538	1532	1492	1482	1602	1650	1566	1700	1482	1536	1481	1483	1485	1531	1653	1540	1507	1547.45	66.65
Tepeu-04	1657		1605	1496		1700	1700			1501		1641	1700			1585			1700		1628.5	80.05
Terevaka-01	1457			1562			1223						1606								1462	171.15

Columns 1-20 refer to seriations containing the following formal variables: 1 - WL,BB,HH; 2 - WL,BB,NC; 3 - WL,BB,EB; 4 - WL,BB,FF; 5 - WL,HH,NC; 6 - WL,HH,EB; 7 - WL,HH,FF; 8 - WL,NC,EB; 9 - WL,NC,FF; 10 - WL,EB,FF; 11 - BB,HH,NC; 12 - BB,HH,EB; 13 - BB,HH,FF; 14 - BB,NC,EB; 15 - BB,NC,FF; 16 - BB,EB,FF; 17 - HH,NC,EB; 18 - HH,NC,FF; 19 - HH,EB,FF; 20 - NC,EB,FF.

146.6 years. Thus, applying some chronometric control to the seriation process decreases variability in results on average by approximately twenty years (12%) for each statue. This may allow for more confidence in these results.

Rather than comparing each of these twenty seriations to the corresponding three-variable seriations without chronometric constraints, the average statue dates are compared. There appears to be little correlation between the average statue dates produced by the three-variable seriations without chronometric constraints and the average statue dates determined by the three-variable seriations with chronometric constraints ($R^2 = 0.09$). The R^2 value is normally a good indicator of similarity between sets of data. However, in comparing seriation results, the statistic does not necessarily reflect all similarities. For example, comparing the three-variable seriation including variables *WL*, *EB*, and *FF* without chronometric constraints to the same seriation with chronometric constraints, the R^2 value shows almost no correlation ($R^2 = 0.0002$). However, visual inspection of the graph comparing the two seriation results demonstrates much more similarity (see Figure 3.2). While the overall orderings are very different, various substrings of the ordering are nearly identical between the two seriations (points along a straight line are perfectly correlated). Some of these substrings have simply been shifted to a different part of the chronology, and others have been reversed. Like more traditional seriation techniques, the OPS technique may produce accurate relative orderings of artifacts or assemblages. However, without sufficient external chronological information for comparison, seriation techniques have no way to determine which end of the seriation is early and which is late.

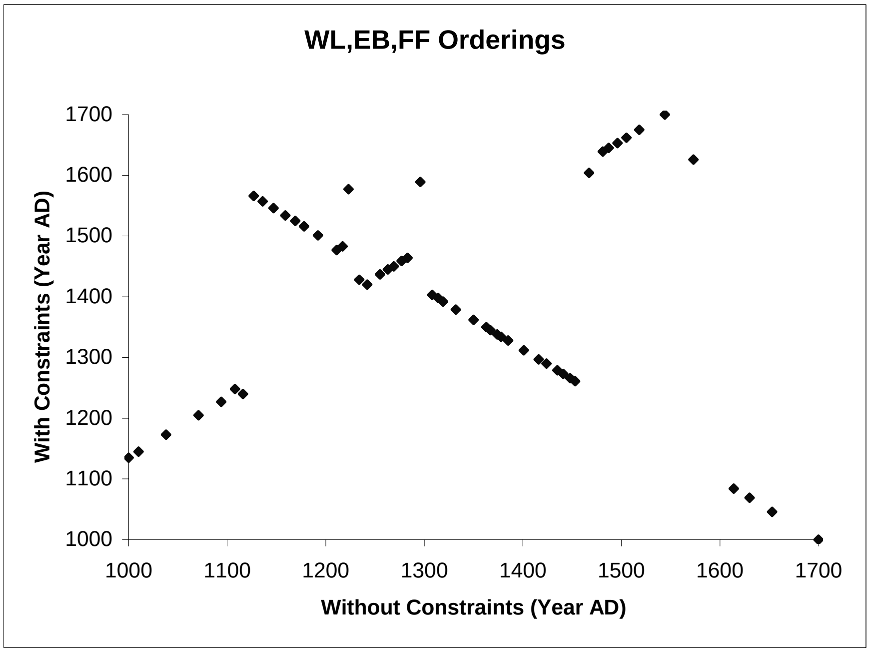


Figure 3.2. Comparison of orderings of statues by the seriation containing variables WL, EB, and FF (with and without chronometric constraints).

Visual inspection of the graph comparing average statue dates for the three-variable seriations with and without chronometric control suggests that even if there is some tendency for points to fall along the diagonals, noise and/or error appear to mask any potential patterns (see Figure 3.3). All points falling precisely on the diagonal would indicate identical chronologies. Unfortunately, no well-known statistic exists to measure the type of variability or similarity that is most important in comparing seriation results. As a secondary measure of similarity, the absolute difference is calculated between the average dates assigned for each statue. The average absolute difference for statue dates between the three-variable seriations with and without chronometric control is 175.2 years. Again, this measure of error or difference is not ideal for comparison of seriation results (as it reflects similarity in absolute dates rather than the relative orderings provided by the seriation), but may supplement the R^2 statistic in an effective manner. In general, the low R^2 value and high average absolute difference between the three-variable analysis without chronometric constraints and the three-variable analysis with chronometric constraints suggests that the analysis without chronometric control likely conflicts with known radiocarbon and obsidian hydration dates.

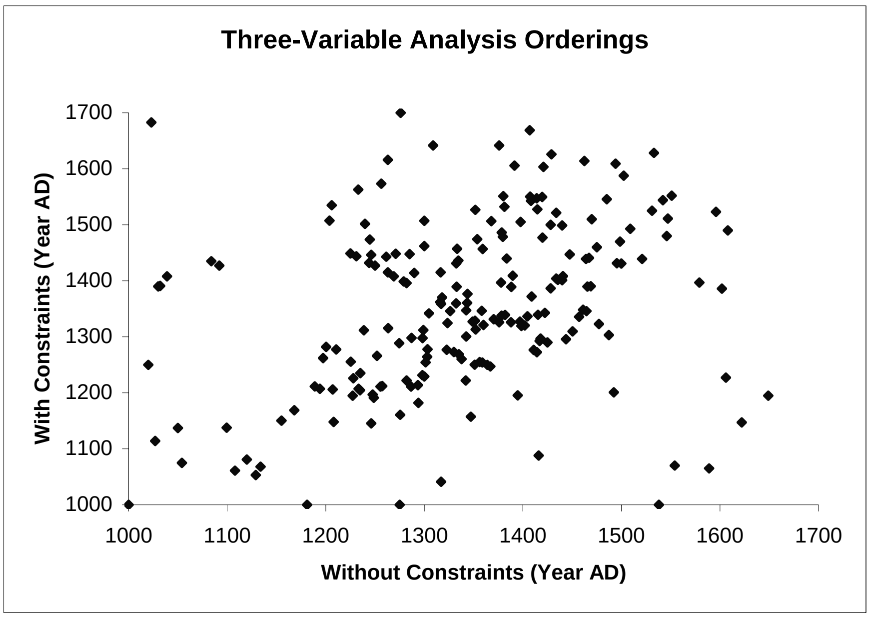


Figure 3.3. Comparison of orderings for statues based on a three-variable approach with and without chronometric constraints.

Seriating with Four Formal Variables (Analysis #3)

Results of four-variable seriations are displayed in Table 3.5. In this case the total possible number of seriations, or combinations of four formal variables, is fifteen. Overall, 122 statues appear in at least one seriation. The advantage of including a fourth formal variable is that some statues whose positions in the chronology that may have

Table 3.5. Four-variable optimal path seriation results (Analysis #3).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
02-209-02																	
02-209-03																	
02-209-04	1443	1325	1347	1413	1389	1479	1534	1616	1466	1197	1385	1457	1511	1630	1217	1427.27	124.79
02-210-02																	
02-210-06			1329													1329	
02-228-01										1700						1700	
03-077-01	1205	1186	1482	1189	1589	1222	1409	1141	1199	1550	1126	1290	1354	1387	1505	1322.27	156.38
05-080-01	1537	1554	1571	1700	1700	1000	1700	1078	1044	1040	1000	1700	1000	1052	1000	1311.73	320.27
05-197-01(R)																	
06-191-01																	
06-255-05																	
07-200-01																	
07-575-04																	
07-581-01				1301	1232	1334				1442				1562		1374.2	129.48
07-584-01										1406						1406	
07-584-02					1161											1161	
07-584-03				1276	1212	1434				1382				1483		1357.4	111.82
07-584-09					1310											1310	
07-584-14																	
08-001-01(R)																	
08-002-01(R)																	
08-003-02(R)				1000												1000	
08-003-05(R)																	
08-345-01	1280	1093	1108	1446	1119	1577	1173	1438	1310	1309	1089	1266	1318	1231	1589	1289.73	164.53
10-020-01																	
11-205-01																	
12-076-01			1365													1365	
12-220-01				1435	1144	1523				1216				1254		1314.4	158.45
12-323-01						1320										1320	
12-397-01																	
12-447-01						1545										1545	
12-452-01																	
12-460-01					1251											1251	
12-460-03				1261	1184	1413				1417				1510		1357	131.61
12-460-04				1251	1192	1404				1428				1523		1359.6	135.31
13-052-01		1137														1137	
13-096-01		1159														1159	
13-331-01					1131											1131	
13-332-01																	
13-403-01																	
13-477-01			1445													1445	
13-478-01		1340	1299			1449			1352				1462			1380.4	71.47
13-481-01			1094													1094	
13-485-01			1496													1496	
13-486-01			1455													1455	
13-487-01		1282	1269			1394			1437				1528			1382	108.69
13-488-01			1389													1389	
13-490-01						1269										1269	
13-492-01																	
13-593-01			1377													1377	
14-021-01					1347											1347	
14-021-02			1397													1397	

Table 3.5. (Continued) Analysis #3.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
14-021-03					1000											1000	
14-159-01						1352										1352	
14-160-01																	
14-463-02	1141	1511	1524	1657	1563	1555	1647	1274	1275	1285	1066	1228	1300	1218	1574	1387.87	194.48
14-493-02																	
14-548-01(R)	1329	1373		1494			1275				1280					1350.2	89.76
14-548-02(R)		1069														1069	
14-548-03(R)	1245	1117		1468			1208				1169					1241.4	135.27
14-548-04(R)																	
14-548-06(R)	1039	1409		1103			1074				1641					1253.2	262.31
14-548-07(R)	1344	1353		1476			1297				1216					1337.2	94.69
14-548-08(R)	1313	1380		1506			1257				1256					1342.4	104.64
14-548-09(R)																	
14-548-11(R)																	
14-548-12(R)																	
14-548-17	1645	1259	1261	1236	1198	1423	1337	1545	1412	1395	1232	1531	1486	1497	1655	1407.47	150.95
14-548-18																	
14-548-19																	
14-548-20															1080	1080	
18-303-01			1601													1601	
18-350-01																	
Akivi-01(R)				1533												1533	
Akivi-02(R)																	
Akivi-03(R)																	
Akivi-04(R)																	
Akivi-05(R)																	
Akivi-06(R)																	
Akivi-07(R)																	
Ature Huki-01(R)																	
L-01											1591	1120	1150	1145	1127	1226.6	204.08
Mahina-01																	
Mahina-02																	
Mata Ketu-01				1068	1451	1594				1137				1700		1390	278.00
MTM-01						1651										1651	
Museo-01(R)																	
Museo-07															1165	1165	
Nau Nau-01-01(R)				1621												1621	
Nau Nau-01-02(R)				1562												1562	
Nau Nau-01-03(R)				1337												1337	
Nau Nau-01-04(R)				1584												1584	
Nau Nau-01-05(R)																	
Nau Nau-01-10	1610	1595	1212	1638	1664	1023	1596	1000	1000	1000	1464	1000	1064	1000	1051	1261.13	289.57
New Ahu-01						1616										1616	
New Ahu-03	1465		1293		1405			1339				1397				1379.8	65.93
Paro(R)																	
Piti-01			1283													1283	
Poike-06																	
Road-I-03			1438													1438	
Road-I-06	1500		1411		1325			1398				1353				1397.4	66.94
Road-N-Ahu-01			1427													1427	
Road-NW-05				1397	1422	1466				1179				1653		1423.4	169.53
Road-NW-06										1254						1254	

Table 3.5. (Continued) Analysis #3.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
Road-NW-10						1181										1181	
RR-020															1556	1556	
RR-033														1290		1290	
RR-034															1700	1700	
RR-035									1255							1255	
RR-037																	
RR-043															1310	1310	
RR-053																	
RR-054																	
RR-056																	
RR-058															1435	1435	
RR-062															1405	1405	
RR-064										1564						1564	
RR-066									1223							1223	
RR-070										1469						1469	
RR-072															1234	1234	
RR-082															1456	1456	
RR-084															1264	1264	
RR-087																	
RR-091		1468	1165			1069			1094				1209			1201	159.31
RR-092										1207						1207	
RR-096																	
RR-097															1295	1295	
RR-099																	
RR-112										1489						1489	
RR-114						1162										1162	
RR-126															1605	1605	
RR-129	1581	1241	1243	1177	1577	1212	1489	1306	1385	1536	1349	1421	1438	1355	1255	1371	133.49
RR-132					1283											1283	
RR-149	1427	1307	1358	1373	1375	1374	1554	1600	1486	1229	1411	1479	1548	1605	1201	1421.8	124.29
RR-226															1669	1669	
RR-227																	
RR-238																	
RR-241															1489	1489	
RR-242															1645	1645	
RR-251																	
RR-254																	
RR-257																	
RR-258	1174	1209	1556	1208	1645	1241	1444	1180	1137	1639	1302	1646	1388	1412	1327	1367.2	183.28
RR-259																	
RR-261																	
RR-262															1278	1278	
RR-265																	
RR-267										1605						1605	
RR-269																	
RR-271																	
RR-273			1313													1313	
RR-277(R)																	
RR-A-001										1338						1338	
RR-A-006				1153	1550	1138				1519				1325		1337	195.00
RR-A-010																	
RR-A-011																	

Table 3.5. (Continued) Analysis #3.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
RR-A-017																	
RR-A-018															1417	1417	
RR-A-019															1471	1471	
RR-A-021																	
RR-A-022																	
RR-A-027	1660	1214	1547	1224	1627	1230	1354	1211	1152	1597	1273	1615	1403	1437	1423	1397.8	176.79
RR-A-038	1700															1700	
RR-A-044/RR-A-045																	
RR-A-047																	
RR-A-048															1286	1286	
RR-A-062																	
RR-A-071																	
RR-A-072															1390	1390	
RR-A-075/RR-A-076														1457		1457	
RR-A-078															1400	1400	
RR-A-079															1367	1367	
RR-A-080																	
RR-A-088															1445	1445	
RR-A-089	1162	1223	1538	1200	1597	1204	1453	1251	1165	1574	1316	1245	1416	1373	1465	1345.47	152.70
RR-A-093																	
RR-A-099															1340	1340	
RR-A-100					1615											1615	
RR-A-104															1376	1376	
RR-A-105					1089											1089	
RR-A-109	1380		1063		1052			1485				1569				1309.8	239.88
RR-B-09		1700	1645			1295			1594				1700			1586.8	168.98
RR-B-12		1028	1025			1686			1700				1036			1295	363.38
RR-C-01																	
RR-C-06															1622	1622	
RR-C-09																	
RR-C-10																	
RR-C-17																	
RR-C-34										1618						1618	
RR-C-37																	
RR-D-07															1357	1357	
RR-D-14																	
RR-D-24																	
RR-D-30										1355						1355	
RR-D-32																	
RR-D-39																	
RR-D-42																	
RR-D-47							1374	1233	1176	1584					1479	1369.2	168.89
S-001-01	1000	1000	1000	1034	1485	1700	1000	1700	1667	1100	1529	1071	1099	1096	1098	1238.6	284.21
Solo-O1																	
Tepeu-02	1091	1447	1130	1123	1527	1112	1129	1375	1324	1168	1700	1179	1261	1173	1536	1285	190.84
Tepeu-04		1640	1700			1504			1534				1610			1597.6	79.44
Terevaka-01			1512													1512	

Columns 1-15 refer to seriations containing the following formal variables: 1 - WL,BB,HH,NC; 2 - WL,BB,HH,EB; 3 - WL,BB,HH,FF; 4 - WL,BB,NC,EB; 5 - WL,BB,NC,FF; 6 - WL,BB,EB,FF; 7 - WL,HH,NC,EB; 8 - WL,HH,NC,FF; 9 - WL,HH,EB,FF; 10 - WL,NC,EB,FF; 11 - BB,HH,NC,EB; 12 - BB,HH,NC,FF; 13 - BB,HH,EB,FF; 14 - BB,NC,EB,FF; 15 - HH,NC,EB,FF.

been ambiguous or indeterminable with only three variables may be more securely dated with more variables in the analysis. This is because more variable values used to describe a statue make that statue, and its optimal placement in a timeline, more constrained. The disadvantage is that reducing our sample size of analyzable statues decreases our chances of dating a statistically representative sample of statues.

The average standard deviation for each statue's calculated average date across four-variable seriations is 166.8 years. There appears to be little correlation between the four-variable seriations to the three-variable seriations. Comparing to the three-variable seriations without chronometric constraints and with chronometric constraints respectively the R^2 values are 0.007 and 0.01; the average absolute differences between statue dates are 142 and 163.2 years respectively. The results suggest that adding chronometric constraints and adding a fourth variable both may impact the seriation results.

Seriating with Four Formal Variables and Chronometric Constraints (Analysis #4)

Results of four-variable seriations including chronometric constraints are displayed in Table 3.6. The average standard deviation for each statue's calculated average date is 152.6 years. Again, adding chronometric control to the seriation analysis changes the results drastically. The four-variable analysis with chronometric control and the four-variable analysis without chronometric control show little correlation ($R^2 = 0.02$,

Table 3.6. Four-variable optimal path seriation results applying chronometric constraints from Table 3.2 (Analysis #4).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
02-209-02																	
02-209-03																	
02-209-04	1257	1393	1424	1627	1334	1579	1603	1455	1632	1554	1521	1250	1607	1255	1455	1463.07	140.19
02-210-02																	
02-210-06			1453													1453	
02-228-01										1700						1700	
03-077-01	1495	1225	1202	1433	1167	1379	1248	1266	1367	1250	1259	1415	1167	1408	1623	1326.93	131.86
05-080-01	1163	1011	1255	1000	1273	1075	1000	1177	1213	1013	1010	1011	1282	1003	1000	1099.07	113.79
05-197-01(R)																	
06-191-01																	
06-255-05																	
07-200-01																	
07-575-04																	
07-581-01				1542	1682	1670				1527				1528		1589.8	79.03
07-584-01										1429						1429	
07-584-02					1614											1614	
07-584-03				1518	1663	1592				1453				1498		1544.8	82.97
07-584-09					1433											1433	
07-584-14																	
08-001-01(R)																	
08-002-01(R)																	
08-003-02(R)				1114												1114	
08-003-05(R)																	
08-345-01	1420	1321	1495	1225	1113	1264	1474	1653	1477	1120	1224	1438	1200	1619	1648	1379.4	184.49
10-020-01																	
11-205-01																	
12-076-01			1406													1406	
12-220-01				1235	1598	1544				1189				1282		1369.6	187.74
12-323-01						1681										1681	
12-397-01																	
12-447-01						1517										1517	
12-452-01																	
12-460-01					1700											1700	
12-460-03				1503	1636	1608				1418				1576		1548.2	88.11
12-460-04				1493	1644	1615				1407				1588		1549.4	97.73
13-052-01		1278														1278	
13-096-01		1254														1254	
13-331-01					1124											1124	
13-332-01																	
13-403-01																	
13-477-01			1328													1328	
13-478-01		1380	1087			1311			1519				1065			1272.4	194.47
13-481-01			1481													1481	
13-485-01			1188													1188	
13-486-01			1317													1317	
13-487-01		1120	1117			1622			1603				1623			1417	272.61
13-488-01			1382													1382	
13-490-01						1330										1330	
13-492-01																	
13-593-01			1394													1394	
14-021-01					1374											1374	
14-021-02			1375													1375	

Table 3.6. (Continued) Analysis #4.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
14-021-03					1000											1000	
14-159-01						1656										1656	
14-160-01																	
14-463-02	1559	1084	1161	1253	1143	1525	1051	1530	1442	1096	1202	1475	1217	1631	1662	1335.4	216.49
14-493-02																	
14-548-01(R)	1371	1351		1336			1376				1388					1364.4	20.74
14-548-02(R)		1622														1622	
14-548-03(R)	1455	1300		1312			1440				1300					1361.4	78.93
14-548-04(R)																	
14-548-06(R)	1661	1647		1681			1569				1596					1630.8	46.70
14-548-07(R)	1356	1369		1320			1354				1450					1369.8	48.35
14-548-08(R)	1387	1344		1348			1393				1411					1376.6	29.33
14-548-09(R)																	
14-548-11(R)																	
14-548-12(R)																	
14-548-17	1055	1145	1125	1479	1650	1600	1316	1384	1578	1440	1435	1177	1583	1564	1547	1405.2	196.68
14-548-18																	
14-548-19																	
14-548-20															1079	1079	
18-303-01			1285													1285	
18-350-01																	
Akivi-01(R)				1375												1375	
Akivi-02(R)																	
Akivi-03(R)																	
Akivi-04(R)																	
Akivi-05(R)																	
Akivi-06(R)																	
Akivi-07(R)																	
Ature Huki-01(R)																	
L-01											1643	1582	1423	1700	1125	1494.6	231.07
Mahina-01																	
Mahina-02																	
Mata Ketu-01				1048	1485	1247				1603				1150		1306.6	231.64
MTM-01						1187										1187	
Museo-01(R)																	
Museo-07															1163	1163	
Nau Nau-01-01(R)				1288												1288	
Nau Nau-01-02(R)				1201												1201	
Nau Nau-01-03(R)				1577												1577	
Nau Nau-01-04(R)				1180												1180	
Nau Nau-01-05(R)																	
Nau Nau-01-10	1090	1051	1597	1271	1239	1051	1100	1099	1169	1051	1154	1700	1342	1051	1051	1201.07	203.66
New Ahu-01						1223										1223	
New Ahu-03	1235		1093		1318			1554				1309				1301.8	167.32
Paro(R)																	
Piti-01			1103													1103	
Poike-06																	
Road-I-03			1334													1334	
Road-I-06	1200		1361		1446			1614				1352				1394.6	151.32
Road-N-Ahu-01			1345													1345	
Road-NW-05				1643	1458	1294				1568				1194		1431.4	186.67
Road-NW-06										1150						1150	

Table 3.6. (Continued) Analysis #4.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
Road-NW-10						1421										1421	
RR-020															1680	1680	
RR-033														1316		1316	
RR-034															1502	1502	
RR-035									1422							1422	
RR-037																	
RR-043															1363	1363	
RR-053																	
RR-054																	
RR-056																	
RR-058															1333	1333	
RR-062															1235	1235	
RR-064										1273						1273	
RR-066									1391							1391	
RR-070										1382						1382	
RR-072															1438	1438	
RR-082															1312	1312	
RR-084															1408	1408	
RR-087																	
RR-091		1700	1551			1006			1263				1477			1399.4	270.52
RR-092										1198						1198	
RR-096																	
RR-097															1378	1378	
RR-099																	
RR-112										1362						1362	
RR-114						1441										1441	
RR-126															1596	1596	
RR-129	1119	1164	1143	1422	1156	1389	1171	1499	1552	1236	1554	1285	1088	1377	1418	1304.87	163.11
RR-132					1407											1407	
RR-149	1273	1410	1413	1611	1347	1639	1622	1439	1652	1176	1496	1229	1642	1231	1470	1443.33	166.40
RR-226															1533	1533	
RR-227																	
RR-238																	
RR-241															1607	1607	
RR-242															1557	1557	
RR-251																	
RR-254																	
RR-257																	
RR-258	1526	1199	1241	1452	1221	1358	1214	1228	1305	1289	1352	1064	1135	1430	1273	1285.8	122.60
RR-259																	
RR-261																	
RR-262															1394	1394	
RR-265																	
RR-267										1323						1323	
RR-269																	
RR-271																	
RR-273			1437													1437	
RR-277(R)																	
RR-A-001										1497						1497	
RR-A-006				1398	1579	1466				1219				1350		1402.4	133.82
RR-A-010																	
RR-A-011																	

Table 3.6. (Continued) Analysis #4.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
RR-A-017																	
RR-A-018															1291	1291	
RR-A-019															1348	1348	
RR-A-021																	
RR-A-022																	
RR-A-027	1040	1194	1232	1468	1204	1370	1301	1346	1320	1331	1396	1095	1121	1454	1297	1277.93	127.89
RR-A-038	1000															1000	
RR-A-044/RR-A-045																	
RR-A-047																	
RR-A-048															1387	1387	
RR-A-062																	
RR-A-071																	
RR-A-072															1221	1221	
RR-A-075/RR-A-076														1473		1473	
RR-A-078															1231	1231	
RR-A-079															1197	1197	
RR-A-080																	
RR-A-088															1323	1323	
RR-A-089	1538	1184	1223	1444	1176	1397	1206	1305	1332	1263	1366	1459	1108	1394	1354	1316.6	121.57
RR-A-093																	
RR-A-099															1260	1260	
RR-A-100					1192											1192	
RR-A-104															1206	1206	
RR-A-105					1085											1085	
RR-A-109	1320		1062		1049			1700				1140				1254.2	271.64
RR-B-09		1451	1646			1700			1105				1000			1380.4	315.52
RR-B-12		1586	1024			1151			1000				1315			1215.2	242.10
RR-C-01																	
RR-C-06															1580	1580	
RR-C-09																	
RR-C-10																	
RR-C-17																	
RR-C-34										1310						1310	
RR-C-37																	
RR-D-07															1243	1243	
RR-D-14																	
RR-D-24																	
RR-D-30										1480						1480	
RR-D-32																	
RR-D-39																	
RR-D-42																	
RR-D-47							1281	1323	1343	1344					1340	1326.2	26.66
S-001-01	1700	1560	1000	1081	1517	1136	1700	1000	1032	1633	1092	1630	1374	1104	1097	1310.4	281.31
Solo-O1																	
Tepeu-02	1609	1682	1516	1700	1557	1494	1516	1591	1492	1577	1700	1524	1527	1674	1700	1590.6	80.86
Tepeu-04		1505	1700			1559			1700				1700			1632.8	93.98
Terevaka-01			1172													1172	

Columns 1-15 refer to seriations containing the following formal variables: 1 - WL,BB,HH,NC; 2 - WL,BB,HH,EB; 3 - WL,BB,HH,FF; 4 - WL,BB,NC,EB; 5 - WL,BB,NC,FF; 6 - WL,BB,EB,FF; 7 - WL,HH,NC,EB; 8 - WL,HH,NC,FF; 9 - WL,HH,EB,FF; 10 - WL,NC,EB,FF; 11 - BB,HH,NC,EB; 12 - BB,HH,NC,FF; 13 - BB,HH,EB,FF; 14 - BB,NC,EB,FF; 15 - HH,NC,EB,FF.

average absolute difference for statue dates = 149.6 years). The correlation between the four-variable analysis with chronometric control and the three-variable analysis with chronometric control, on the other hand, is considerably stronger ($R^2 = 0.33$, average absolute difference for statue dates = 87.6 years). This correlation suggests that once the seriations are constrained by existing chronometric information, adding a fourth variable influences the optimal ordering of statues relatively little. This correlation may also give us some confidence in the validity of results when including chronometric constraints.

Seriating without Quarry Statues (Analyses #5 and #6)

The seriation analysis to this point has included as many statues as possible, given the information required by the three- or four-variable approach. In the case of the three-variable analysis, 93 out of 203 statues analyzed (46%) are statues that still reside in the immediate vicinity of the Rano Raraku statue quarry. In the case of the four-variable analysis, 43 out of 122 statues analyzed (35%) are statues that still reside in the quarry area. Today, nearly 400 statues are located in the quarry area and remain in various stages of completion. Some are only roughly hewn and still securely fastened to the natural bedrock. Others are detached, and some stand erected on the interior and exterior slopes of the volcanic crater that forms the quarry. Reviewing Tables 3.2 through 3.6, seriation analyses assign average dates to quarry statues (those whose names begin with RR) that span the 700 year spectrum. Thus, one possibility is that statues that reside in the quarry today were actually constructed throughout prehistory, and perhaps some were not intended to be carved completely or moved outside of the quarry area.

There is also the second possibility that statues that reside in the quarry today were still in the process of construction when the statue tradition finally came to an end on the island. If this were the case, there is little justification to include and analyze these unfinished statues in terms of their formal characteristics. Determining which statues in the quarry area (let alone the rest of the island) were complete based on which statues the islanders intended for further carving is impossible. Therefore, in order to exclude unfinished *moai* from the analysis in a systematic and relatively objective manner, the "quarry" designation is based on geographical distinctions devised by Cristino et al. in 1981. This spatial division is somewhat arbitrary, and admittedly may have the unintended consequence of removing some statues from the analysis that are indeed completed statues. Nevertheless, the net effect of the geographic restriction is the desired one. All quarry statues are removed from the data set and three- and four-variable analyses with chronometric constraints are recalculated. Tables 3.7 and 3.8 display the results of seriations omitting quarry statues.

For the three-variable analysis with chronometric constraints, omitting quarry statues (46% of the data set) has relatively little effect on the average dates assigned by the OPS algorithm. Chronometrically-informed three-variable analyses with quarry statues and without appear to be highly correlated ($R^2 = 0.66$, average absolute difference for statue dates = 66.8 years). Furthermore, the three-variable seriation analysis omitting quarry statues offers an average standard deviation for each statue's calculated average date of 150.5 years—slightly worse than the chronometrically-constrained three-variable analysis *with* quarry statues.

Table 3.7. Chronometrically-constrained three-variable optimal path seriation results omitting quarry statues (Analysis #5).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
02-209-02													1250								1250	
02-209-03																	1576				1576	
02-209-04	1563	1300	1383	1700	1631	1406	1562	1376	1408	1465	1543	1317	1579	1640	1625	1579	1353	1346	1597	1266	1481.95	133.49
02-210-02																			1080		1080	
02-210-06								1635						1618			1590			1601	1611	19.71
02-228-01	1000										1000	1136	1409								1136.25	192.80
03-077-01	1069	1438	1510	1571	1219	1316	1314	1538	1497	1256	1377	1591	1552	1209	1348	1232	1123	1448	1233	1127	1348.4	162.95
05-080-01	1357	1126	1700	1013	1017	1220	1051	1129	1217	1047	1265	1000	1219	1161	1161	1170	1191	1026	1194	1075	1166.95	157.72
05-197-01(R)																			1375		1375	
06-191-01																	1663				1663	
06-255-05																	1639				1639	
07-200-01																	1425				1425	
07-575-04																	1362				1362	
07-581-01	1627				1700	1532	1660				1620	1527	1527				1680	1658	1534		1606.5	69.69
07-584-01	1667										1436	1477	1536								1529	100.74
07-584-02						1456						1428					1609		1445		1484.5	83.80
07-584-03	1700				1668	1505	1631				1603	1511	1476				1482	1611	1513		1570	82.01
07-584-09						1590						1637					1669		1575		1617.75	43.18
07-584-14					1423																1423	
08-001-01(R)																			1014		1014	
08-002-01(R)																			1398		1398	
08-003-02(R)							1100						1700					1174	1700		1418.5	326.45
08-003-05(R)																			1321		1321	
08-345-01	1136	1506	1478	1499	1391	1344	1278	1502	1280	1234	1089	1364	1026	1473	1438	1433	1086	1284	1273	1357	1323.55	149.77
10-020-01														1345							1345	
11-205-01																	1219				1219	
12-076-01								1352						1631			1334			1287	1401	155.76
12-220-01	1582				1545	1432	1286				1534	1399	1012				1598	1489	1262		1413.9	182.85
12-323-01					1289						1408						1691	1646			1508.5	191.91
12-397-01																			1205		1205	
12-447-01					1517						1653						1538	1517			1556.25	65.26
12-452-01																	1204				1204	
12-460-01						1554						1567					1700		1554		1593.75	71.10
12-460-03	1649				1642	1475	1610				1443	1490	1501				1500	1469	1500		1527.9	75.73
12-460-04	1608				1604	1484	1594				1456	1547	1515				1505	1383	1490		1518.6	71.72
13-052-01									1339						1377			1619		1425	1440	124.41
13-096-01									1334						1323			1397		1091	1286.25	134.19
13-331-01						1354						1382					1096		1286		1279.5	128.80
13-332-01																				1189	1189	
13-403-01											1520										1520	
13-477-01								1244						1282			1405			1054	1246.25	145.42
13-478-01		1376			1246			1438	1431		1584			1395	1601		1464	1603		1313	1445.1	121.80
13-481-01								1497						1446			1073			1528	1386	211.39
13-485-01								1515						1233			1524			1136	1352	197.46
13-486-01								1229						1265			1437			1066	1249.25	152.19
13-487-01		1272			1616			1390	1387		1464			1327	1240		1493	1373		1197	1375.9	126.10
13-488-01								1320						1581			1647			1036	1396	278.45
13-490-01					1261						1393						1446	1630			1432.5	152.93
13-492-01											1387										1387	
13-593-01								1333						1601			1344			1303	1395.25	138.26
14-021-01						1089						1662					1632		1170		1388.25	300.85
14-021-02								1308						1569			1655			1030	1390.5	282.01

Table 3.7. (Continued) Analysis #5.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
14-021-03						1002						1446					1308		1038		1198.5	214.18
14-159-01					1329						1665						1388	1676			1514.5	181.79
14-160-01														1248							1248	
14-463-02	1150	1229	1452	1476	1404	1334	1264	1476	1598	1206	1645	1610	1168	1292	1216	1117	1529	1507	1244	1158	1353.75	171.29
14-493-02																	1264				1264	
14-548-01(R)				1353			1338		1455	1380			1374		1577	1393		1589	1316	1339	1411.4	98.17
14-548-02(R)									1611						1477			1300		1568	1489	137.83
14-548-03(R)				1531			1590		1311	1300			1333		1411	1300		1358	1300	1382	1381.6	102.47
14-548-04(R)																			1328		1328	
14-548-06(R)				1669			1502		1645	1578			1609		1641	1627		1567	1645	1612	1609.5	49.13
14-548-07(R)				1385			1601		1368	1405			1344		1518	1379		1350	1306	1327	1398.3	91.78
14-548-08(R)				1327			1355		1466	1357			1453		1569	1359		1582	1343	1345	1415.6	96.36
14-548-09(R)				1364																	1364	
14-548-11(R)				1425																	1425	
14-548-12(R)				1300																	1300	
14-548-17	1686	1339	1000	1341	1657	1491	1620	1403	1441	1398	1425	1538	1492	1315	1278	1002	1510	1461	1496	1181	1403.7	185.64
14-548-18									1000												1000	
14-548-19		1198																			1198	
14-548-20	1335	1026	1229	1148																	1184.5	130.49
18-303-01								1176						1131			1244			1000	1137.75	102.91
18-350-01																	1413				1413	
Akivi-01(R)							1390						1361					1552	1422		1431.25	84.27
Akivi-02(R)																			1435		1435	
Akivi-03(R)																			1365		1365	
Akivi-04(R)																			1450		1450	
Akivi-05(R)																			1357		1357	
Akivi-06(R)																			1378		1378	
Akivi-07(R)																			1461		1461	
Ature Huki-01(R)																			1680		1680	
L-01	1484	1579	1311	1079	1454	1700	1454	1000	1061	1630											1375.2	251.12
Mahina-01																				1205	1205	
Mahina-02																				1593	1593	
Mata Ketu-01	1442				1368	1135	1011				1106	1245	1636				1062	1091	1139		1223.5	199.11
MTM-01					1135						1157						1000	1132			1106	71.54
Museo-01(R)				1255																	1255	
Museo-07	1119	1616	1072	1224																	1257.75	247.14
Nau Nau-01-01(R)							1232						1301					1069	1289		1222.75	106.83
Nau Nau-01-02(R)							1194						1051					1264	1409		1229.5	148.92
Nau Nau-01-03(R)							1700						1108					1700	1051		1389.75	359.00
Nau Nau-01-04(R)							1159						1084					1234	1393		1217.5	132.06
Nau Nau-01-05(R)																			1350		1350	
Nau Nau-01-10	1286	1054	1158	1191	1051	1271	1224	1076	1156	1146	1288	1051	1142	1101	1101	1053	1177	1051	1479	1236	1164.6	110.01
New Ahu-01					1165						1061						1047	1314			1146.75	123.30
New Ahu-03			1429			1382		1448		1084		1339		1385		1545	1469		1601	1317	1399.9	141.56
Paro(R)																				1108	1108	
Piti-01								1425						1366			1476			1212	1369.75	114.37
Poike-06																				1512	1512	
Road-I-03								1247						1298			1399			1045	1247.25	148.89
Road-I-06			1581			1603		1287		1016		1301		1546		1479	1379		1586	1405	1418.3	183.57
Road-N-Ahu-01								1264						1522			1674			1019	1369.75	288.65
Road-NW-05	1536				1682	1615	1545				1557	1283	1594				1369	1337	1109		1462.7	179.98
Road-NW-06	1193										1700	1405	1289								1396.75	219.96

Table 3.7. (Continued) Analysis #5.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
Road-NW-10					1201						1354						1143	1428			1281.5	132.14
RR-020																						
RR-033																						
RR-034																						
RR-035																						
RR-037																						
RR-043																						
RR-053																						
RR-054																						
RR-056																						
RR-058																						
RR-062																						
RR-064																						
RR-066																						
RR-070																						
RR-072																						
RR-082																						
RR-084																						
RR-087																						
RR-091																						
RR-092																						
RR-096																						
RR-097																						
RR-099																						
RR-112																						
RR-114																						
RR-126																						
RR-129																						
RR-132																						
RR-149																						
RR-226																						
RR-227																						
RR-238																						
RR-241																						
RR-242																						
RR-251																						
RR-254																						
RR-257																						
RR-258																						
RR-259																						
RR-261																						
RR-262																						
RR-265																						
RR-267																						
RR-269																						
RR-271																						
RR-273																						
RR-277(R)																						
RR-A-001																						
RR-A-006																						
RR-A-010																						
RR-A-011																						

Table 3.7. (Continued) Analysis #5.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Ave	St Dev
RR-A-017																						
RR-A-018																						
RR-A-019																						
RR-A-021																						
RR-A-022																						
RR-A-027																						
RR-A-038																						
RR-A-044/RR-A-045																						
RR-A-047																						
RR-A-048																						
RR-A-062																						
RR-A-071																						
RR-A-072																						
RR-A-075/RR-A-076																						
RR-A-078																						
RR-A-079																						
RR-A-080																						
RR-A-088																						
RR-A-089																						
RR-A-093																						
RR-A-099																						
RR-A-100																						
RR-A-104																						
RR-A-105																						
RR-A-109																						
RR-B-09																						
RR-B-12																						
RR-C-01																						
RR-C-06																						
RR-C-09																						
RR-C-10																						
RR-C-17																						
RR-C-34																						
RR-C-37																						
RR-D-07																						
RR-D-14																						
RR-D-24																						
RR-D-30																						
RR-D-32																						
RR-D-39																						
RR-D-42																						
RR-D-47																						
S-001-01	1386	1000	1270	1127	1089	1179	1088	1043	1123	1542	1197	1201	1664	1000	1000	1700	1030	1208	1663	1649	1257.95	249.29
Solo-O1																				1549	1549	
Tepeu-02	1520	1481	1615	1617	1488	1680	1481	1580	1550	1700	1569	1700	1602	1483	1541	1496	1555	1539	1632	1483	1565.6	73.56
Tepeu-04		1700			1573			1700	1700		1494			1700	1700		1618	1484		1700	1636.9	89.52
Terevaka-01								1488						1502			1107			1453	1387.5	188.13

Columns 1-20 refer to seriations containing the following formal variables: 1 - WL,BB,HH; 2 - WL,BB,NC; 3 - WL,BB,EB; 4 - WL,BB,FF; 5 - WL,HH,NC; 6 - WL,HH,EB; 7 - WL,HH,FF; 8 - WL,NC,EB; 9 WL,NC,FF; 10 - WL,EB,FF; 11 - BB,HH,NC; 12 - BB,HH,EB; 13 - BB,HH,FF; 14 - BB,NC,EB; 15 - BB,NC,FF; 16 - BB,EB,FF; 17 - HH,NC,EB; 18 - HH,NC,FF; 19 - HH,EB,FF; 20 - NC,EB,FF.

Table 3.8. Chronometrically-constrained four-variable optimal path seriation results omitting quarry statues (Analysis #6).

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
02-209-02																	
02-209-03																	
02-209-04	1491	1289	1312	1279	1510	1526	1630	1582	1571	1442	1356	1374	1351	1436	1326	1431.67	114.87
02-210-02																	
02-210-06													1647			1647	
02-228-01						1282										1282	
03-077-01	1632	1348	1441	1453	1292	1700	1430	1330	1208	1374	1092	1572	1497	1208	1142	1381.27	176.89
05-080-01	1000	1000	1000	1000	1000	1000	1195	1000	1000	1021	1007	1006	1120	1002	1201	1036.8	72.23
05-197-01(R)																	
06-191-01																	
06-255-05																	
07-200-01																	
07-575-04																	
07-581-01		1700				1661				1533	1573	1660				1625.4	69.49
07-584-01						1607										1607	
07-584-02											1648					1648	
07-584-03		1659				1640				1423	1593	1633				1589.6	96.19
07-584-09											1439					1439	
07-584-14																	
08-001-01(R)																	
08-002-01(R)																	
08-003-02(R)												1245				1245	
08-003-05(R)																	
08-345-01	1578	1394	1229	1481	1247	1193	1526	1403	1459	1267	1160	1122	1587	1332	1512	1366	155.96
10-020-01																	
11-205-01																	
12-076-01													1331			1331	
12-220-01		1577				1540				1649	1664	1110				1508	228.26
12-323-01										1517						1517	
12-397-01																	
12-447-01										1674						1674	
12-452-01																	
12-460-01											1554					1554	
12-460-03		1625				1593				1602	1622	1611				1610.6	13.43
12-460-04		1608				1577				1591	1614	1600				1598	14.58
13-052-01														1274		1274	
13-096-01														1247		1247	
13-331-01											1142					1142	
13-332-01																	
13-403-01																	
13-477-01													1221			1221	
13-478-01			1378				1583			1476			1384	1418		1447.8	85.01
13-481-01													1608			1608	
13-485-01													1478			1478	
13-486-01													1207			1207	
13-487-01			1289				1325			1581			1420	1139		1350.8	163.65
13-488-01													1298			1298	
13-490-01										1495						1495	
13-492-01																	
13-593-01													1315			1315	
14-021-01											1388					1388	
14-021-02													1288			1288	

Table 3.8. (Continued) Analysis #6.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
14-021-03											1499					1499	
14-159-01										1553						1553	
14-160-01																	
14-463-02	1551	1411	1204	1507	1221	1109	1287	1278	1142	1295	1112	1090	1455	1091	1101	1256.93	159.17
14-493-02																	
14-548-01(R)					1421				1347			1426		1376	1396	1393.2	32.74
14-548-02(R)														1642		1642	
14-548-03(R)					1342				1421			1398		1300	1467	1385.6	65.69
14-548-04(R)																	
14-548-06(R)					1576				1609			1526		1534	1646	1578.2	50.57
14-548-07(R)					1459				1319			1407		1403	1375	1392.6	51.12
14-548-08(R)					1400				1366			1439		1364	1416	1397	32.34
14-548-09(R)																	
14-548-11(R)																	
14-548-12(R)																	
14-548-17	1418	1643	1347	1209	1439	1622	1367	1216	1269	1408	1607	1620	1431	1169	1008	1384.87	188.50
14-548-18																	
14-548-19																	
14-548-20	1188															1188	
18-303-01													1162			1162	
18-350-01																	
Akivi-01(R)												1467				1467	
Akivi-02(R)																	
Akivi-03(R)																	
Akivi-04(R)																	
Akivi-05(R)																	
Akivi-06(R)																	
Akivi-07(R)																	
Ature Huki-01(R)																	
L-01	1091	1471	1578	1640	1634											1482.8	229.28
Mahina-01																	
Mahina-02																	
Mata Ketu-01		1198				1443				1243	1271	1318				1294.6	93.70
MTM-01										1166						1166	
Museo-01(R)																	
Museo-07	1340															1340	
Nau Nau-01-01(R)												1051				1051	
Nau Nau-01-02(R)												1148				1148	
Nau Nau-01-03(R)												1700				1700	
Nau Nau-01-04(R)												1173				1173	
Nau Nau-01-05(R)																	
Nau Nau-01-10	1253	1064	1068	1103	1165	1053	1128	1107	1087	1051	1051	1070	1078	1054	1051	1092.2	55.40
New Ahu-01										1212						1212	
New Ahu-03				1319				1539			1334		1376		1300	1373.6	96.60
Paro(R)																	
Piti-01													1401			1401	
Poike-06																	
Road-I-03													1231			1231	
Road-I-06				1372				1459			1417		1269		1256	1354.6	89.65
Road-N-Ahu-01													1246			1246	
Road-NW-05		1261				1502				1457	1309	1358				1377.4	100.58
Road-NW-06						1152										1152	

Table 3.8. (Continued) Analysis #6.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
Road-NW-10										1346						1346	
RR-020																	
RR-033																	
RR-034																	
RR-035																	
RR-037																	
RR-043																	
RR-053																	
RR-054																	
RR-056																	
RR-058																	
RR-062																	
RR-064																	
RR-066																	
RR-070																	
RR-072																	
RR-082																	
RR-084																	
RR-087																	
RR-091																	
RR-092																	
RR-096																	
RR-097																	
RR-099																	
RR-112																	
RR-114																	
RR-126																	
RR-129																	
RR-132																	
RR-149																	
RR-226																	
RR-227																	
RR-238																	
RR-241																	
RR-242																	
RR-251																	
RR-254																	
RR-257																	
RR-258																	
RR-259																	
RR-261																	
RR-262																	
RR-265																	
RR-267																	
RR-269																	
RR-271																	
RR-273																	
RR-277(R)																	
RR-A-001																	
RR-A-006																	
RR-A-010																	
RR-A-011																	

Table 3.8. (Continued) Analysis #6.

Name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Ave	St Dev
RR-A-017																	
RR-A-018																	
RR-A-019																	
RR-A-021																	
RR-A-022																	
RR-A-027																	
RR-A-038																	
RR-A-044/RR-A-045																	
RR-A-047																	
RR-A-048																	
RR-A-062																	
RR-A-071																	
RR-A-072																	
RR-A-075/RR-A-076																	
RR-A-078																	
RR-A-079																	
RR-A-080																	
RR-A-088																	
RR-A-089																	
RR-A-093																	
RR-A-099																	
RR-A-100																	
RR-A-104																	
RR-A-105																	
RR-A-109																	
RR-B-09																	
RR-B-12																	
RR-C-01																	
RR-C-06																	
RR-C-09																	
RR-C-10																	
RR-C-17																	
RR-C-34																	
RR-C-37																	
RR-D-07																	
RR-D-14																	
RR-D-24																	
RR-D-30																	
RR-D-32																	
RR-D-39																	
RR-D-42																	
RR-D-47																	
S-001-01	1151	1134	1117	1700	1094	1394	1000	1700	1700	1115	1223	1281	1000	1700	1700	1333.93	285.08
Solo-O1																	
Tepeu-02	1700	1510	1510	1572	1700	1487	1501	1491	1507	1700	1700	1506	1557	1583	1582	1573.73	84.95
Tepeu-04			1700				1700			1628			1700	1487		1643	92.61
Terevaka-01													1527			1527	

Columns 1-15 refer to seriations containing the following formal variables: 1 - WL,BB,HH,NC; 2 - WL,BB,HH,EB; 3 - WL,BB,HH,FF; 4 - WL,BB,NC,EB; 5 - WL,BB,NC,FF; 6 - WL,BB,EB,FF; 7 - WL,HH,NC,EB; 8 - WL,HH,NC,FF; 9 - WL,HH,EB,FF; 10 - WL,NC,EB,FF; 11 - BB,HH,NC,EB; 12 - BB,HH,NC,FF; 13 - BB,HH,EB,FF; 14 - BB,NC,EB,FF; 15 - HH,NC,EB,FF.

Similarly, omitting quarry statues (35% of the data set) has only a small effect on the four-variable analysis. Chronometrically-informed four-variable analyses with quarry statues and without show a positive correlation as well ($R^2 = 0.45$, average absolute difference for statue dates = 94.6 years). On the other hand, the four-variable seriation analysis omitting quarry statues offers an average standard deviation for each statue's calculated average date of 107.4 years—a significant decrease from the chronometrically-constrained four-variable analysis *with* quarry statues. This decrease suggests that quarry statues produce a fair amount of noise in the four-variable analysis with chronometric constraints.

Results in both the three-variable and four-variable approach when omitting quarry statues give some indication of the robustness of the OPS analysis using chronometric constraints and may in turn increase confidence in the results. The possibility that quarry statues remain unfinished (i.e. unfit for analysis of formal variability) along with the indication that quarry statues are producing unwanted noise in the analysis imply that the most accurate results may be those that omit statues that still reside in the quarry.

Reconsidering Variables (Analyses #7 and #8)

Despite some agreement between the three-variable analyses with dates and the four-variable analyses with dates, the average standard deviation for statues' calculated dates within each analysis is still quite large (146 and 152 years respectively). Omitting quarry statue appears to improve this statistic considerably in the four-variable approach, reducing the value to 107 years. There is a possibility, however, as the three-variable analysis uses twenty combinations of three formal variables and the four-variable analysis uses fifteen combinations of four formal variables, that certain variables or combinations of variables may be more desirable than others for seriation. In other words, certain variables may conform more precisely to the assumptions of OPS while others are merely producing noise or errors. Those variables most fit for seriation analysis, if isolated and analyzed, may produce more consistent (in terms of the average standard deviation) and accurate results.

In an attempt to identify problematic variables, each individual three-variable seriation is compared to each of the four-variable seriations that contain the same initial three variables. For example, seriation results from the three-variable seriation (Analysis #2) containing variables *WL*, *BB*, and *HH* are compared to: (1) the four-variable seriation (Analysis #4) containing *WL*, *BB*, *HH*, and *NC*; (2) the four-variable seriation (Analysis #4) containing *WL*, *BB*, *HH*, and *EB*; and (3) the four-variable seriation (Analysis #4) containing *WL*, *BB*, *HH*, and *FF*. Table 3.9 compares three-variable seriation results to four-variable seriation results (all seriations calculated with chronometric constraints). Each value in the table signifies the average absolute difference (in years) between statue dates assigned by the three-variable analysis and statue dates assigned by the four-variable recalculation.

The idea behind the comparisons is that an optimal and accurate three-variable seriation should show relatively little change (i.e. show a relatively small average absolute difference) when a fourth variable is included and the seriation is recalculated. However, specific variables that do not conform to the assumptions of OPS may render

Table 3.9. Average absolute difference for statues (in years) when a fourth variable is added to a three-variable seriation and results are recalculated.

	WL	BB	HH	NC	EB	FF	Seriation Average
HH,EB,FF	75.17	196.67		73.74			115.19
WL,BB,HH				117.52	119.39	149.11	128.67
WL,EB,FF		115.58	136.26	146.12			132.65
WL,HH,NC		166.17			49.00	186.78	133.98
WL,NC,FF		158.24	168.11		123.32		149.89
BB,HH,NC	177.57				77.75	218.94	158.09
WL,NC,EB		198.82	140.70			139.15	159.56
WL,HH,EB		199.50		152.95		127.22	159.89
BB,EB,FF	75.78		268.76	135.68			160.07
BB,HH,FF	209.89			102.72	188.52		167.05
HH,NC,EB	182.90	198.05				125.77	168.91
HH,NC,FF	139.56	226.78			140.47		168.93
WL,BB,FF			229.66	147.50	133.58		170.25
WL,BB,EB			221.79	156.42		157.86	178.69
WL,BB,NC			202.74		159.64	176.12	179.50
NC,EB,FF	205.15	193.36	150.53				183.01
WL,HH,FF		152.79		170.22	237.57		186.86
BB,NC,FF	146.94		238.50		176.84		187.43
BB,HH,EB	160.96			164.00		256.81	193.92
BB,NC,EB	212.15		201.65			177.92	197.24
Variable Average	158.61	180.60	195.87	136.69	140.61	171.57	
St Dev	50.49	32.07	45.27	30.21	54.28	41.65	

consistently high average absolute differences, regardless of the accuracy or optimality of the three-variable seriation. The far right hand column may be an indicator of the reliability of each seriation—the lower the average value, the better. The two bottom rows of the table may be indicators of the fitness of each individual formal variable to be used in OPS analysis. Unfortunately, the table provides no conclusive answers.

Variables *BB* and *HH* both show relatively high average values overall (180.6 and 195.9 respectively) with relatively low standard deviations. These statistics may indicate that adding these variables onto a three-variable seriation to form a four-variable seriation consistently produces major changes in the chronological ordering of statue construction events. If this were the case, *BB* and *HH* are variables undesirable for seriation analysis. Variables *WL* and *EB*, on the other hand, show much lower average values with relatively high standard deviations. These statistics may indicate that there are very good three-variable seriations (ones whose chronological orderings change little when *WL* or *EB* is added to make a four-variable seriation), and there are very bad three-variable seriations (ones whose chronological orderings change drastically when *WL* or *EB* is added to make a four-variable seriation). Results for variables *FF* and *NC* are difficult to interpret. The mid-range values of *FF* offer little significant information. The extremely low average value and low standard deviation of *NC* may have one of the following two indications. First, the fact that *NC* consistently produces only relatively minor changes when added onto three-variable seriations may suggest that all of the three-variable seriations are good ones. However, the other variables in the analysis appear not to agree with such an interpretation. A second possibility is that *NC* offers little potential for seriating, and when included has little impact on the optimal ordering.

Although there may not be clear statistical support to guide further manipulation of the data based on Table 3.9, one final step is taken based on interpretations of the table values. Using *WL* and *EB* as the most reliable variables for seriation, specific four-variable seriations are isolated from the table. Cases in which *WL* or *EB* are added onto three-variable seriations to form four variable seriations and neither one produces an average absolute difference greater than 152.6 (the average standard deviation for statue dates from the four-variable analysis with chronometric constraints) years are gathered together. For example, from row 1 of Table 3.9, the four-variable seriation containing *WL*, *HH*, *EB*, and *FF* is selected. From row 2, the four-variable seriation containing *WL*, *BB*, *HH*, and *EB* is selected. From row 4, the four-variable seriation containing *WL*, *HH*, *NC*, and *EB* is selected. From row 5, the four-variable seriation containing *WL*, *NC*, *EB*,

Table 3.10. Chronometrically-constrained four-variable optimal path seriation results–based on Tables 3.8 and 3.9 (Analysis #7).

Name	1	2	3	4	5	6	7	8	Ave	St Dev
02-209-02										
02-209-03										
02-209-04	1289	1510	1630	1582	1571	1374	1351	1326	1454.13	133.53
02-210-02										
02-210-06							1647		1647	
02-228-01										
03-077-01	1348	1292	1430	1330	1208	1572	1497	1142	1352.38	143.65
05-080-01	1000	1000	1195	1000	1000	1006	1120	1201	1065.25	91.65
05-197-01(R)										
06-191-01										
06-255-05										
07-200-01										
07-575-04										
07-581-01	1700					1660			1680	28.28
07-584-01										
07-584-02										
07-584-03	1659					1633			1646	18.38
07-584-09										
07-584-14										
08-001-01(R)										
08-002-01(R)										
08-003-02(R)						1245			1245	
08-003-05(R)										
08-345-01	1394	1247	1526	1403	1459	1122	1587	1512	1406.25	154.59
10-020-01										
11-205-01										
12-076-01							1331		1331	
12-220-01	1577					1110			1343.5	330.22
12-323-01										
12-397-01										
12-447-01										
12-452-01										
12-460-01										
12-460-03	1625					1611			1618	9.90
12-460-04	1608					1600			1604	5.66
13-052-01										
13-096-01										
13-331-01										
13-332-01										
13-403-01										
13-477-01							1221		1221	
13-478-01			1583				1384		1483.5	140.71
13-481-01							1608		1608	
13-485-01							1478		1478	
13-486-01							1207		1207	
13-487-01			1325				1420		1372.5	67.18
13-488-01							1298		1298	
13-490-01										
13-492-01										
13-593-01							1315		1315	
14-021-01										
14-021-02							1288		1288	

Table 3.10. (Continued) Analysis #7.

Name	1	2	3	4	5	6	7	8	Ave	St Dev
14-021-03										
14-159-01										
14-160-01										
14-463-02	1411	1221	1287	1278	1142	1090	1455	1101	1248.13	136.47
14-493-02										
14-548-01(R)		1421			1347	1426		1396	1397.5	36.13
14-548-02(R)										
14-548-03(R)		1342			1421	1398		1467	1407	51.97
14-548-04(R)										
14-548-06(R)		1576			1609	1526		1646	1589.25	50.95
14-548-07(R)		1459			1319	1407		1375	1390	58.64
14-548-08(R)		1400			1366	1439		1416	1405.25	30.67
14-548-09(R)										
14-548-11(R)										
14-548-12(R)										
14-548-17	1643	1439	1367	1216	1269	1620	1431	1008	1374.13	210.56
14-548-18										
14-548-19										
14-548-20										
18-303-01							1162		1162	
18-350-01										
Akivi-01(R)						1467			1467	
Akivi-02(R)										
Akivi-03(R)										
Akivi-04(R)										
Akivi-05(R)										
Akivi-06(R)										
Akivi-07(R)										
Ature Huki-01(R)										
L-01	1471	1634							1552.5	115.26
Mahina-01										
Mahina-02										
Mata Ketu-01	1198					1318			1258	84.85
MTM-01										
Museo-01(R)										
Museo-07										
Nau Nau-01-01(R)						1051			1051	
Nau Nau-01-02(R)						1148			1148	
Nau Nau-01-03(R)						1700			1700	
Nau Nau-01-04(R)						1173			1173	
Nau Nau-01-05(R)										
Nau Nau-01-10	1064	1165	1128	1107	1087	1070	1078	1051	1093.75	37.79
New Ahu-01										
New Ahu-03				1539			1376	1300	1405	122.11
Paro(R)										
Piti-01							1401		1401	
Poike-06										
Road-I-03							1231		1231	
Road-I-06				1459			1269	1256	1328	113.64
Road-N-Ahu-01							1246		1246	
Road-NW-05	1261					1358			1309.5	68.59
Road-NW-06										

Table 3.10. (Continued) Analysis #7.

Name	1	2	3	4	5	6	7	8	Ave	St Dev
Road-NW-10										
RR-020										
RR-033										
RR-034										
RR-035										
RR-037										
RR-043										
RR-053										
RR-054										
RR-056										
RR-058										
RR-062										
RR-064										
RR-066										
RR-070										
RR-072										
RR-082										
RR-084										
RR-087										
RR-091										
RR-092										
RR-096										
RR-097										
RR-099										
RR-112										
RR-114										
RR-126										
RR-129										
RR-132										
RR-149										
RR-226										
RR-227										
RR-238										
RR-241										
RR-242										
RR-251										
RR-254										
RR-257										
RR-258										
RR-259										
RR-261										
RR-262										
RR-265										
RR-267										
RR-269										
RR-271										
RR-273										
RR-277(R)										
RR-A-001										
RR-A-006										
RR-A-010										
RR-A-011										

Table 3.10. (Continued) Analysis #7.

Name	1	2	3	4	5	6	7	8	Ave	St Dev
RR-A-017										
RR-A-018										
RR-A-019										
RR-A-021										
RR-A-022										
RR-A-027										
RR-A-038										
RR-A-044/RR-A-045										
RR-A-047										
RR-A-048										
RR-A-062										
RR-A-071										
RR-A-072										
RR-A-075/RR-A-076										
RR-A-078										
RR-A-079										
RR-A-080										
RR-A-088										
RR-A-089										
RR-A-093										
RR-A-099										
RR-A-100										
RR-A-104										
RR-A-105										
RR-A-109										
RR-B-09										
RR-B-12										
RR-C-01										
RR-C-06										
RR-C-09										
RR-C-10										
RR-C-17										
RR-C-34										
RR-C-37										
RR-D-07										
RR-D-14										
RR-D-24										
RR-D-30										
RR-D-32										
RR-D-39										
RR-D-42										
RR-D-47										
S-001-01	1134	1094	1000	1700	1700	1281	1000	1700	1326.13	321.80
Solo-O1										
Tepeu-02	1510	1700	1501	1491	1507	1506	1557	1582	1544.25	70.28
Tepeu-04			1700				1700		1700	0.00
Terevaka-01							1527		1527	

Columns 1-8 refer to seriations containing the following formal variables: 1 - BB,NC,EB,FF; 2 - BB,HH,NC,EB; 3 - WL,HH,EB,FF; 4 - WL,HH,NC,FF; 5 - WL,HH,NC,EB; 6 - WL,BB,NC,EB; 7 - WL,BB,HH,FF; 8 - WL,BB,HH,NC.

and *FF* is selected. From row 9, the four-variable seriation containing *WL*, *BB*, *EB*, and *FF* is selected. From row 12, the four-variable seriation containing *WL*, *HH*, *NC*, and *FF* is selected. And from row 12, the four-variable seriation containing *HH*, *NC*, *EB*, and *FF* is also selected. These seven specific four-variable seriations based on information from Table 3.9 are used to recalculate average dates for statue construction events in Table 3.10. The average standard deviation for each statue's calculated average date based on these seven seriations is 145.2 years.

Statistics were also calculated to compare three-variable seriations and four-variable seriations for analyses in which quarry statues were omitted. Results are presented in Table 3.11. In this case, the only variable that seems to be an outlier is *HH* (head depth: head width) with an average value of 171 years. A likely explanation for

Table 3.11. Average absolute difference for statues (in years) when a fourth variable is added to a three-variable seriation and results are recalculated. All seriations omit quarry statues.

	WL	BB	HH	NC	EB	FF	Seriation Average
WL,BB,HH				86.38	90.50	172.75	116.54
WL,BB,NC			173.44		205.00	189.92	189.45
WL,BB,EB			174.15	105.19		116.85	132.06
WL,BB,FF			165.82	130.13	125.58		140.51
WL,HH,NC		80.06			58.36	69.18	69.20
WL,HH,EB		159.85		134.36		44.92	113.04
WL,HH,FF		129.89		134.36	50.83		105.03
WL,NC,EB		159.04	119.00			150.00	142.68
WL,NC,FF		129.21	212.82		156.05		166.03
WL,EB,FF		120.27	152.83	194.95			156.02
BB,HH,NC	146.69				56.67	174.75	126.03
BB,HH,EB	153.50			132.53		131.54	139.19
BB,HH,FF	30.29			175.25	137.08		114.20
BB,NC,EB	108.04		95.73			103.24	102.34
BB,NC,FF	164.92		185.58		144.53		165.01
BB,EB,FF	129.73		154.38	74.24			119.45
HH,NC,EB	144.21	152.07				70.92	122.40
HH,NC,FF	216.45	192.00			197.92		202.12
HH,EB,FF	72.25	48.54		206.58			109.12
NC,EB,FF	110.63	154.76	276.00				180.47
Variable Average	127.67	132.57	170.98	137.40	122.25	122.41	
St Dev	51.43	41.95	49.45	43.79	56.70	50.07	

the consistently poor results using variable *HH* is that the variable does not conform to the assumptions of OPS and cannot reliably be used in seriation analysis. Therefore, all four-variable seriations that do not contain *HH* are selected to recalculate average dates for statue construction events in Table 3.12. The average standard deviation for each statue's calculated average date from Table 3.12 is 95.4 years.

Discussion

Rapa Nui *moai* are a difficult group of artifacts to date precisely. Although chronometric dates have been determined for some of the *ahu* upon which *moai* likely stood, chronometric dating techniques have been of little use in the direct study of statues. As an alternative, archaeologists have made some effort to recognize different periods of statue construction by formal variability within statues. These efforts have taken the form of statistical or cluster analyses (Van Tilburg 1986). While statistical analyses of statues may identify patterns within statue variability, these patterns have no necessary relation to chronology.

Seriation, on the other hand, is an archaeological method developed explicitly for the study of temporal variability in artifact forms. The concept of seriation has been applied only minimally to Rapa Nui statuary in the past (Shepardson and Hunt 2001). Here however, extensive seriation analysis (150 total seriations) and statistical interpretations of these seriation results have generated eight plausible chronological orderings for statue construction events. Clearly, not all of these orderings can be correct, and the possibility remains that all of these seriations contain inaccuracies.

Table 3.12. Chronometrically-constrained four-variable optimal path seriation—based on Tables 3.7 and 3.10 (Analysis #8).

Name	1	2	3	4	5	Ave	St Dev
02-209-02							
02-209-03							
02-209-04	1289	1526	1442	1356	1374	1397.4	69.52
02-210-02							
02-210-06							
02-228-01		1282				1282	
03-077-01	1348	1700	1374	1092	1572	1417.2	80.58
05-080-01	1000	1000	1021	1007	1006	1006.8	163.70
05-197-01(R)							
06-191-01							
06-255-05							
07-200-01							
07-575-04							
07-581-01	1700	1661	1533	1573	1660	1625.4	69.52
07-584-01		1607				1607	
07-584-02				1648		1648	
07-584-03	1659	1640	1423	1593	1633	1589.6	69.52
07-584-09				1439		1439	
07-584-14							
08-001-01(R)							
08-002-01(R)							
08-003-02(R)					1245	1245	
08-003-05(R)							
08-345-01	1394	1193	1267	1160	1122	1227.2	266.67
10-020-01							
11-205-01							
12-076-01							
12-220-01	1577	1540	1649	1664	1110	1508	66.44
12-323-01			1517			1517	
12-397-01							
12-447-01			1674			1674	
12-452-01							
12-460-01				1554		1554	
12-460-03	1625	1593	1602	1622	1611	1610.6	99.75
12-460-04	1608	1577	1591	1614	1600	1598	99.75
13-052-01							
13-096-01							
13-331-01				1142		1142	
13-332-01							
13-403-01							
13-477-01							
13-478-01			1476			1476	
13-481-01							
13-485-01							
13-486-01							
13-487-01			1581			1581	
13-488-01							
13-490-01			1495			1495	
13-492-01							
13-593-01							
14-021-01				1388		1388	
14-021-02							

Table 3.12. (Continued) Analysis #8.

Name	1	2	3	4	5	Ave	St Dev
14-021-03				1499		1499	
14-159-01			1553			1553	
14-160-01							
14-463-02	1411	1109	1295	1112	1090	1203.4	114.84
14-493-02							
14-548-01(R)					1426	1426	
14-548-02(R)							
14-548-03(R)					1398	1398	
14-548-04(R)							
14-548-06(R)					1526	1526	
14-548-07(R)					1407	1407	
14-548-08(R)					1439	1439	
14-548-09(R)							
14-548-11(R)							
14-548-12(R)							
14-548-17	1643	1622	1408	1607	1620	1580	85.50
14-548-18							
14-548-19							
14-548-20							
18-303-01							
18-350-01							
Akivi-01(R)					1467	1467	
Akivi-02(R)							
Akivi-03(R)							
Akivi-04(R)							
Akivi-05(R)							
Akivi-06(R)							
Akivi-07(R)							
Ature Huki-01(R)							
L-01	1471					1471	
Mahina-01							
Mahina-02							
Mata Ketu-01	1198	1443	1243	1271	1318	1294.6	133.10
MTM-01			1166			1166	
Museo-01(R)							
Museo-07							
Nau Nau-01-01(R)					1051	1051	
Nau Nau-01-02(R)					1148	1148	
Nau Nau-01-03(R)					1700	1700	
Nau Nau-01-04(R)					1173	1173	
Nau Nau-01-05(R)							
Nau Nau-01-10	1064	1053	1051	1051	1070	1057.8	143.48
New Ahu-01			1212			1212	
New Ahu-03				1334		1334	
Paro(R)							
Piti-01							
Poike-06							
Road-I-03							
Road-I-06				1417		1417	
Road-N-Ahu-01							
Road-NW-05	1261	1502	1457	1309	1358	1377.4	222.37
Road-NW-06		1152				1152	

Table 3.12. (Continued) Analysis #8.

Name	1	2	3	4	5	Ave	St Dev
Road-NW-10			1346			1346	
RR-020							
RR-033							
RR-034							
RR-035							
RR-037							
RR-043							
RR-053							
RR-054							
RR-056							
RR-058							
RR-062							
RR-064							
RR-066							
RR-070							
RR-072							
RR-082							
RR-084							
RR-087							
RR-091							
RR-092							
RR-096							
RR-097							
RR-099							
RR-112							
RR-114							
RR-126							
RR-129							
RR-132							
RR-149							
RR-226							
RR-227							
RR-238							
RR-241							
RR-242							
RR-251							
RR-254							
RR-257							
RR-258							
RR-259							
RR-261							
RR-262							
RR-265							
RR-267							
RR-269							
RR-271							
RR-273							
RR-277(R)							
RR-A-001							
RR-A-006							
RR-A-010							
RR-A-011							

Table 3.12. (Continued) Analysis #8.

Name	1	2	3	4	5	Ave	St Dev
RR-A-017							
RR-A-018							
RR-A-019							
RR-A-021							
RR-A-022							
RR-A-027							
RR-A-038							
RR-A-044/RR-A-045							
RR-A-047							
RR-A-048							
RR-A-062							
RR-A-071							
RR-A-072							
RR-A-075/RR-A-076							
RR-A-078							
RR-A-079							
RR-A-080							
RR-A-088							
RR-A-089							
RR-A-093							
RR-A-099							
RR-A-100							
RR-A-104							
RR-A-105							
RR-A-109							
RR-B-09							
RR-B-12							
RR-C-01							
RR-C-06							
RR-C-09							
RR-C-10							
RR-C-17							
RR-C-34							
RR-C-37							
RR-D-07							
RR-D-14							
RR-D-24							
RR-D-30							
RR-D-32							
RR-D-39							
RR-D-42							
RR-D-47							
S-001-01	1134	1394	1115	1223	1281	1229.4	95.35
Solo-O1							
Tepeu-02	1510	1487	1700	1700	1506	1580.6	86.17
Tepeu-04			1628			1628	
Terevaka-01							

Columns 1-5 refer to seriations containing the following formal variables: 1 - BB,NC,EB,FF; 2 - WL,BB,EB,FF; 3 - WL,BB,NC,EB; 4 - WL,BB,NC,FF; 5 - WL,NC,EB,FF.

However, the results of the analysis are the best possible based on current knowledge of *ahu* construction dates and the method chosen for analysis.

Tables 3.13 and 3.14 summarize results from the eight possible chronologies derived through seriation analysis. In each step of the analysis, measures were taken in an attempt to improve the quality of the results (mostly in terms of the average standard deviation value for dates assigned to each statue). *R*-squared tests between each two seriation orderings (displayed on the right side of Table 3.13) suggest that results are generally correlated, and although the analysis offers several chronological orderings for the statues, these orderings contain extensive similarities. The only two orderings that

Table 3.13. Comparison of optimal path seriation analysis results.

Analysis Number	Number of Variables	Chronometric Constraints Using *Ahu* Dates	Quarry Statues Included	Number of Statues	Average Standard Deviation	R-squared values between seriation analysis orderings							
						1	2	3	4	5	6	7	8
1	3	no	yes	203	166.5	1	0.092	0.007	0.145	0.045	0.136	0.182	0.251
2	3	yes	yes	203	146.6		1	0.01	0.33	0.66	0.491	0.394	0.436
3	4	no	yes	122	166.8			1	0.019	0.026	0.029	0.078	0.013
4	4	yes	yes	122	152.6				1	0.424	0.447	0.743	0.49
5	3	yes	no	110	150.5					1	0.611	0.408	0.586
6	4	yes	no	68	107.4						1	0.497	0.912
7	4	yes	yes	89	145.2							1	0.415
8	4	yes	no	49	95.4								1

appear not to be correlated with the others are the analyses in which no chronometric constraints were employed (Analyses #1 and #3). This result is of no surprise, and these two orderings may be ruled out as potential chronologies for further consideration.

The correlation between the six remaining chronometrically-constrained seriation analyses is, to some extent, reassuring. Despite manipulation of certain parameters, omission of quarry statues, and differential treatment for different variables or combinations of variables, the OPS algorithm finds orderings that are largely consistent

Table 3.14. Summary of optimal path seriation results.

Name	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
02-209-02	1680		1250						1250							
02-209-03	1098		1386						1576							
02-209-04	1225	168.9	1460	139.3	1427	124.8	1463	140.2	1482	133.5	1432	114.9	1524	89.92	1397	90.19
02-210-02	1284		1088						1080							
02-210-06	1202	141.3	1470	144.4	1329		1453		1611	19.71	1647					
02-228-01	1473	330.2	1195	222.7	1700		1700		1136	192.8	1282		1700		1282	
03-077-01	1377	176.2	1325	136.1	1322	156.4	1327	131.9	1348	162.9	1381	176.9	1337	140	1417	232.6
05-080-01	1425	261.9	1161	167.5	1312	320.3	1099	113.8	1167	157.7	1037	72.23	1070	89.86	1007	8.585
05-197-01(R)	1421		1399						1375							
06-191-01	1293		1669						1663							
06-255-05	1154		1480						1639							
07-200-01	1437		1616						1425							
07-575-04	1179		1439						1362							
07-581-01	1238	120.3	1614	61.97	1374	129.5	1590	79.03	1607	69.69	1625	69.49	1599	101.1	1625	69.49
07-584-01	1272	92.81	1500	48.08	1406		1429		1529	100.7	1607		1429		1607	
07-584-02	1266	157.7	1522	123.4	1161		1614		1485	83.8	1648				1648	
07-584-03	1293	135.9	1550	98.67	1357	111.8	1545	82.97	1570	82.01	1590	96.19	1523	98.29	1590	96.19
07-584-09	1279	217.2	1604	41.39	1310		1433		1618	43.18	1439				1439	
07-584-14	1153		1511						1423							
08-001-01(R)	1146		1070						1014							
08-002-01(R)	1383		1359						1398							
08-003-02(R)	1496	332.5	1508	237.9	1000		1114		1419	326.4	1245				1245	
08-003-05(R)	1340		1321						1321							
08-345-01	1367	170.6	1390	167.4	1290	164.5	1379	184.5	1324	149.8	1366	156	1422	198.6	1227	107.4
10-020-01	1413		1298						1345							
11-205-01	1406		1182						1219							
12-076-01	1236	84.05	1346	105.4	1365		1406		1401	155.8	1331					
12-220-01	1233	129.8	1441	171.7	1314	158.4	1370	187.7	1414	182.8	1508	228.3	1367	251	1508	228.3
12-323-01	1309	62.28	1606	137.8	1320		1681		1509	191.9	1517		1681		1517	
12-397-01	1051		1195						1205							
12-447-01	1444	189.1	1574	52.37	1545		1517		1556	65.26	1674		1517		1674	
12-452-01	1646		1075						1204							
12-460-01	1198	120.7	1588	38.33	1251		1700		1594	71.1	1554				1554	
12-460-03	1292	128.5	1543	87.44	1357	131.6	1548	88.11	1528	75.73	1611	13.43	1513	134.4	1611	13.43
12-460-04	1280	122.4	1550	87.8	1360	135.3	1549	97.73	1519	71.72	1598	14.58	1511	147.1	1598	14.58
13-052-01	1280	149.2	1477	127	1137		1278		1440	124.4	1274		1278			
13-096-01	1285	117	1339	119.6	1159		1254		1286	134.2	1247		1254			
13-331-01	1437	88.76	1316	81.18	1131		1124		1280	128.8	1142				1142	
13-332-01	1592		1061						1189							
13-403-01	1169		1525						1520							
13-477-01	1298	113.3	1320	222.1	1445		1328		1246	145.4	1221					
13-478-01	1368	153.1	1360	174	1380	71.47	1272	194.5	1445	121.8	1448	85.01	1403	105.9	1476	
13-481-01	1332	226.3	1507	97.11	1094		1481		1386	211.4	1608					
13-485-01	1429	220.6	1449	180.9	1496		1188		1352	197.5	1478					
13-486-01	1353	178.8	1157	16.8	1455		1317		1249	152.2	1207					
13-487-01	1278	174.5	1343	179.1	1382	108.7	1417	272.6	1376	126.1	1351	163.6	1448	284.5	1581	
13-488-01	1231	61.73	1390	219.5	1389		1382		1396	278.4	1298					
13-490-01	1374	111.8	1346	225	1269		1330		1433	152.9	1495		1330		1495	
13-492-01	1448		1266						1387							
13-593-01	1283	191.5	1293	197.7	1377		1394		1395	138.3	1315					
14-021-01	1243	283.1	1336	255.2	1347		1374		1388	300.9	1388				1388	
14-021-02	1235	57.52	1390	219	1397		1375		1391	282	1288					

Table 3.14. (Continued) Summary of optimal path seriation results.

Name	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
14-021-03	1213	153.4	1303	340.2	1000		1000		1199	214.2	1499				1499	
14-159-01	1342	115.5	1347	266.5	1352		1656		1515	181.8	1553		1656		1553	
14-160-01	1506		1207						1248							
14-463-02	1356	190.4	1377	213.4	1388	194.5	1335	216.5	1354	171.3	1257	159.2	1341	255.9	1203	142.8
14-493-02	1358		1222						1264							
14-548-01(R)	1415	168.8	1448	120.8	1350	89.76	1364	20.74	1411	98.17	1393	32.74	1364	17.68	1426	
14-548-02(R)	1460	124.8	1502	122.9	1069		1622		1489	137.8	1642		1622			
14-548-03(R)	1366	156.3	1436	121.7	1241	135.3	1361	78.93	1382	102.5	1386	65.69	1370	98.99	1398	
14-548-04(R)	1351		1327						1328							
14-548-06(R)	1320	229.3	1551	126.8	1253	262.3	1631	46.7	1610	49.13	1578	50.57	1608	55.15	1526	
14-548-07(R)	1454	173.2	1446	132.1	1337	94.69	1370	48.35	1398	91.78	1393	51.12	1362	10.61	1407	
14-548-08(R)	1455	158.4	1474	119	1342	104.6	1377	29.33	1416	96.36	1397	32.34	1369	34.65	1439	
14-548-09(R)	1236		1439						1364							
14-548-11(R)	1424		1700						1425							
14-548-12(R)	1391		1642						1300							
14-548-17	1316	168.3	1440	175.6	1407	150.9	1405	196.7	1404	185.6	1385	188.5	1430	163.8	1580	97.01
14-548-18	1519		1000						1000							
14-548-19	1191		1493						1198							
14-548-20	1601	104.7	1138	88.7	1080		1079		1185	130.5	1188		1079			
18-303-01	1492	200.5	1148	92.41	1601		1285		1138	102.9	1162					
18-350-01	1324		1642						1413							
Akivi-01(R)	1341	210	1457	89.91	1533		1375		1431	84.27	1467				1467	
Akivi-02(R)	1437		1415						1435							
Akivi-03(R)	1456		1432						1365							
Akivi-04(R)	1450		1427						1450							
Akivi-05(R)	1475		1449						1357							
Akivi-06(R)	1418		1396						1378							
Akivi-07(R)	1431		1408						1461							
Ature Huki-01(R)	1677		1683						1680							
L-01	1461	199.1	1312	218.3	1227	204.1	1495	231.1	1375	251.1	1483	229.3	1125		1471	
Mahina-01	1580		1081						1205							
Mahina-02	1324		1326						1593							
Mata Ketu-01	1322	282.9	1338	237.8	1390	278	1307	231.6	1224	199.1	1295	93.7	1425	251.7	1295	93.7
MTM-01	1208	330.4	1201	58.64	1651		1187		1106	71.54	1166		1187		1166	
Museo-01(R)	1532		1169						1255							
Museo-07	1545	30.83	1150	62.82	1165		1163		1258	247.1	1340		1163			
Nau Nau-01-01(R)	1451	143.9	1191	120.7	1621		1288		1223	106.8	1051				1051	
Nau Nau-01-02(R)	1500	98.38	1282	108.9	1562		1201		1230	148.9	1148				1148	
Nau Nau-01-03(R)	1289	257.7	1277	305.4	1337		1577		1390	359	1700				1700	
Nau Nau-01-04(R)	1503	120.2	1262	116.5	1584		1180		1218	132.1	1173				1173	
Nau Nau-01-05(R)	1469		1444						1350							
Nau Nau-01-10	1454	196.6	1145	96.56	1261	289.6	1201	203.7	1165	110	1092	55.4	1082	44.77	1058	8.701
New Ahu-01	1256	227.4	1296	61.57	1616		1223		1147	123.3	1212		1223		1212	
New Ahu-03	1349	163.5	1328	190.8	1380	65.93	1302	167.3	1400	141.6	1374	96.6	1554		1334	
Paro(R)	1078		1147						1108							
Piti-01	1426	137.3	1289	141.4	1283		1103		1370	114.4	1401					
Poike-06	1494		1535						1512							
Road-I-03	1302	116.7	1320	224.6	1438		1334		1247	148.9	1231					
Road-I-06	1252	176.9	1447	200	1397	66.94	1395	151.3	1418	183.6	1355	89.65	1614		1417	
Road-N-Ahu-01	1303	123.5	1327	223.6	1427		1345		1370	288.7	1246					
Road-NW-05	1200	152.7	1431	197.3	1423	169.5	1431	186.7	1463	180	1377	100.6	1431	193.7	1377	100.6
Road-NW-06	1400	283.6	1507	224.4	1254		1150		1397	220	1152		1150		1152	

Table 3.14. (Continued) Summary of optimal path seriation results.

Name	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
Road-NW-10	1395	238.3	1342	157.5	1181		1421		1282	132.1	1346		1421		1346	
RR-020	1272	199.1	1387	201.9	1556		1680						1680			
RR-033	1367	210.1	1457	143	1290		1316									
RR-034	1158	70.49	1544	80.11	1700		1502						1502			
RR-035	1382	223.7	1370	234.1	1255		1422						1422			
RR-037	1700		1000													
RR-043	1259	111.4	1408	68.91	1310		1363						1363			
RR-053	1650		1137													
RR-054	1291		1372													
RR-056	1094		1227													
RR-058	1250	84.09	1310	197.9	1435		1333						1333			
RR-062	1443	104.4	1212	89.9	1405		1235						1235			
RR-064	1362	211.7	1261	180.3	1564		1273						1273			
RR-066	1410	143.2	1414	183.4	1223		1391						1391			
RR-070	1358	163.5	1301	269.5	1469		1382						1382			
RR-072	1230	269.3	1510	116.2	1234		1438						1438			
RR-082	1286	122.1	1273	172.8	1456		1312						1312			
RR-084	1368	196.4	1431	76.54	1264		1408						1408			
RR-087	1566		1068													
RR-091	1475	272.4	1256	256.5	1201	159.3	1399	270.5					1323	350.9		
RR-092	1205	161.2	1431	237.6	1207		1198						1198			
RR-096	1400		1229													
RR-097	1260	139.6	1401	106.3	1295		1378						1378			
RR-099	1322		1397													
RR-112	1348	172.1	1527	106.7	1489		1362						1362			
RR-114	1384	246.6	1362	157.6	1162		1441						1441			
RR-126	1346	177.9	1474	128.5	1605		1596						1596			
RR-129	1377	165.4	1277	129	1371	133.5	1305	163.1					1347	157.4		
RR-132	1322	246.2	1486	190.5	1283		1407									
RR-149	1223	169.3	1323	216.2	1422	124.3	1443	166.4					1487	170.2		
RR-226	1285	159.1	1528	183.2	1669		1533						1533			
RR-227	1271		1626													
RR-238	1149		1552													
RR-241	1295	71.67	1337	204.6	1489		1607						1607			
RR-242	1319	149.1	1532	173.3	1645		1557						1557			
RR-251	1425		1000													
RR-254	1104		1523													
RR-257	1341		1254													
RR-258	1402	191.7	1231	115.1	1367	183.3	1286	122.6					1267	56.57		
RR-259	1215		1546													
RR-261	1162		1000													
RR-262	1384	183.4	1415	44.53	1278		1394						1394			
RR-265	1571		1053													
RR-267	1414	107.9	1211	139.6	1605		1323						1323			
RR-269	1266		1404													
RR-271	1275		1290													
RR-273	1358	106.8	1347	44.59	1313		1437									
RR-277(S)	1111		1065													
RR-A-001	1320	170.5	1479	99.81	1338		1497						1497			
RR-A-006	1439	188	1443	145.5	1337	195	1402	133.8					1343	174.7		
RR-A-010	1673		1114													
RR-A-011	1318		1339													

Table 3.14. (Continued) Summary of optimal path seriation results.

Name	1a	1b	2a	2b	3a	3b	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
RR-A-017	1401		1312													
RR-A-018	1407	117.3	1214	114	1417		1291						1291			
RR-A-019	1402	178	1298	152.5	1471		1348						1348			
RR-A-021	1121		1397													
RR-A-022	1282		1297													
RR-A-027	1397	173.3	1278	149	1398	176.8	1278	127.9					1308	56.46		
RR-A-038	1330	241.5	1331	163.5	1700		1000									
RR-A-044/RR-A-04	1472		1226													
RR-A-047	1670		1390													
RR-A-048	1265	138.9	1402	103.7	1286		1387						1387			
RR-A-062	1336		1250													
RR-A-071	1333		1247													
RR-A-072	1399	100.5	1255	99.71	1390		1221						1221			
RR-A-075/RR-A-07	1312	143.2	1389	135.7	1457		1473									
RR-A-078	1445	104.3	1211	85.14	1400		1231						1231			
RR-A-079	1467	75.02	1207	55.61	1367		1197						1197			
RR-A-080	1608		1427													
RR-A-088	1305	109.5	1196	168.5	1445		1323						1323			
RR-A-089	1397	187.7	1264	140.8	1345	152.7	1317	121.6					1292	78.04		
RR-A-093	1370		1273													
RR-A-099	1511	160.1	1212	141.7	1340		1260						1260			
RR-A-100	1490	169.1	1278	165.6	1615		1192									
RR-A-104	1465	79.94	1205	64.04	1376		1206						1206			
RR-A-105	1239	126.4	1349	57.81	1089		1085									
RR-A-109	1348	215.3	1313	207	1310	239.9	1254	271.6					1700			
RR-B-09	1310	268.9	1409	304.2	1587	169	1380	315.5					1419	298.8		
RR-B-12	1349	290.2	1250	206.8	1295	363.4	1215	242.1					1246	304.3		
RR-C-01	1365		1269													
RR-C-06	1260	68.51	1499	132	1622		1580						1580			
RR-C-09	1616		1435													
RR-C-10	1092		1490													
RR-C-17	1493		1206													
RR-C-34	1418	99.24	1222	135.4	1618		1310						1310			
RR-C-37	1661		1408													
RR-D-07	1453	87.78	1197	77.02	1357		1243						1243			
RR-D-14	1465		1235													
RR-D-24	1312		1326													
RR-D-30	1302	164.8	1505	81.57	1355		1480						1480			
RR-D-32	1206		1609													
RR-D-39	1383		1041													
RR-D-42	1668		1391													
RR-D-47	1344	150	1255	151.9	1369	168.9	1326	26.66					1326	26.66		
S-001-01	1356	281.7	1361	245.5	1239	284.2	1310	281.3	1258	249.3	1334	285.1	1308	307.7	1229	114
Solo-O1	1467		1563						1549							
Tepeu-02	1286	230.4	1547	66.65	1285	190.8	1591	80.86	1566	73.56	1574	84.95	1579	85.79	1581	109.3
Tepeu-04	1167	217.8	1629	80.05	1598	79.44	1633	93.98	1637	89.52	1643	92.61	1588	100.7	1628	
Terevaka-01	1400	242.6	1462	171.2	1512		1172		1388	188.1	1527					

Columns 1 - 8 refer to results for statue dates (a) and standard deviation values (b) for the following analyses: 1 - Table 3.2; 2 - Table 3.3; 3 - Table 3.4; 4 - Table 3.5; 5 - Table 3.6; 6 - Table 3.7; 7 - Table 3.9; 8 - Table 3.11.

with one another. Ideally, these orderings are all correlated with one another because they are all correlated with time.

Even after removing Analyses #1 and #3 from further consideration, results do not necessarily provide precision satisfactory for a foundation for detailed subsequent analysis. The average standard deviation values ranging from approximately 95 to 153 years dictate the scale at which the chronology may be scrutinized. On the other hand, the average standard deviation values may be, in some cases, larger than they should be. Certain statues that display particularly large standard deviation values in some of the analyses (e.g. 14-463-02, Nau Nau-01-10, RR-129, S-001-01) may do so not because they have been dated at a variety of points throughout the chronology, but because they may be dated both at the beginning of the chronology and toward the end. Therefore, the average value falls in the middle of the time frame and the standard deviation is relatively high. In such a case, neither the average value nor the standard deviation value is particularly meaningful.

For some of the statues with extremely high standard deviation values, no further evidence is available for comparison. In the case of statue S-001-01, however, contextual evidence may help to determine the chronological placement more accurately and precisely. S-001-01 is a short, squat basalt statue on the north coast of the island in the context of *ahu* Heu. Throughout seriation analyses, S-001-01 is placed either in the first couple centuries of the timeline or in the last couple centuries, but rarely in between. Approximately three kilometers southwest of S-001-01 lies another short, squat basalt statue, MTM-01. Not only are these two statues related spatially and by their material, but formally, the statues appear to be similar. Appearing in twenty seriations together (out of the total 150), the statues were dated on average 52.5 years apart. At greatest, the statues were dated 93 years apart. Therefore, there may be ample reason to believe that these statues were constructed around the same time. MTM-01 is currently built into the rear retaining wall of *ahu* Maitake Te Moa, implying that the statue was constructed prior to the final construction episode of the *ahu*. This context suggests some time depth for statue MTM-01, but little in terms of a precise position in the chronology. However, the fact that MTM-01 is dated consistently within the initial two centuries of the chronology by seriation analyses may indicate that S-001-01 should be as well. In most cases, relevant contextual dates or evidence for statues remains uncollected.

Another way to improve seriation results may be to account for formal variability in artifacts attributable to space rather than time (e.g. Cochrane 2001, Lipo et al. 1997). Isolating and omitting quarry statues may be one solution to this problem, and omitting quarry statues from the analysis appears to reduce the average standard deviation value significantly in the four-variable approach.

Although there was likely social and political division of space on the island (e.g., Routledge 1914; Stevenson 1984, 2002; Shepardson 2005a), statues were not differentiated spatially in the preceding analysis for two reasons. The first reason is practical. Reducing seriation analyses to statues within a sociopolitical territory or statues based on a windward/leeward distinction would reduce sample size so drastically that seriations may no longer reflect a complete or thorough chronology. The second reason is that nearly all statues (95%) were carved from the rim of the same volcanic crater. From the point of view of cultural transmission, the proximity with which statues were constructed seems to ensure that ideas and styles were transmitted regularly, even if unintentionally.

Selecting a Statue Chronology

Omitting Analyses #1 and #3, six possible chronologies of *moai* construction dates remain for further consideration (Analyses 2, 4, 5, 6, 7, and 8 from Table 3.13). However, some or all of these chronologies likely contain inaccuracies. Optimal path seriation, like any traditional seriation technique, can produce problematic orderings for a number of reasons. First, there is inevitably some degree of error in the initial data collection. In some cases, erosion to statues prevents accurate measurements. In other cases, statues are now partially buried or in other precarious postures that make certain formal features unreachable. Second, even extremely minor spatial variability in statue construction that is unaccounted for in the analysis may confound temporal seriation results. Third, previously published radiocarbon dates from research on *ahu* were used in the seriation analysis to loosely bracket possible construction dates for individual statues. These radiocarbon dates (or their context within the *ahu*, or even the relationship between a statue and a particular phase of construction of an *ahu*) may be problematic due to issues in research executed long prior to the analysis presented here. And finally, the variables used throughout the seriation analysis and the statues themselves, may not conform to requisite assumptions of optimal path seriation.

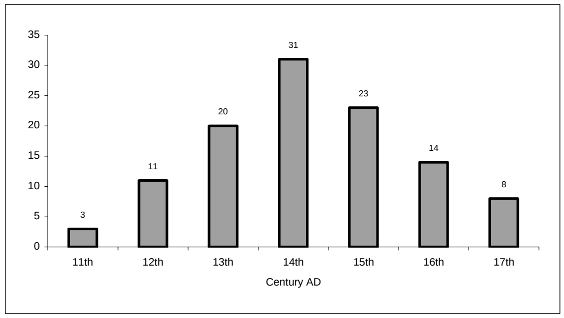
Despite the potential sources of error in the analysis, the chronologies derived in the previous chapter may contain important information. They constitute the best chronological orderings of *moai* possible, given the selected method and existing data. Even so, elimination of some of these results is desirable for two reasons. First, eliminating several of the chronological results helps to simplify and facilitate further analyses based on statue chronology. Second, while all six of the potential chronologies may contain inaccuracies, one of these is likely to be more accurate than the others. Identifying one set of results above all others may help to ensure the quality of further analysis based on *moai* chronology.

Logical reasoning and objective statistical analysis are used to eliminate five out of the six potential chronological orderings. Those analyses including statues that reside in the context of the Rano Raraku statue quarry are excluded first (Analyses 2, 4, and 7). As discussed in the previous chapter, there is reason to believe that the vast majority of statues located in the quarry area may not be complete. Some are still securely attached to the natural bedrock. Furthermore, there may be statues in the quarry area that were complete, or at least partially complete, but were abandoned because they contained stylistic aberrations or manufacturing defects. Both incomplete statues and stylistic aberrations can present serious problems in a seriation analysis. To avoid these problems, our attention is restricted to the three remaining analyses that omitted quarry statues.

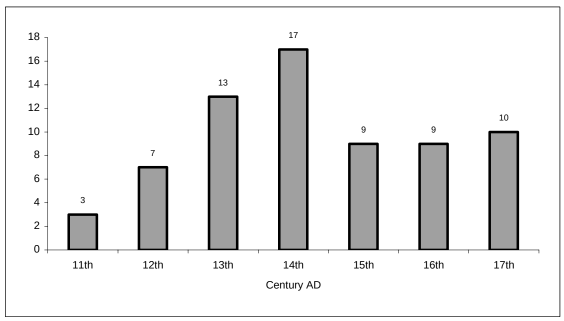
The three remaining analyses are numbers 5, 6, and 8 from Table 3.13. These correspond respectively to a chronometrically-constrained three-variable analysis omitting quarry statues, a chronometrically-constrained four-variable analysis omitting quarry statues, and a chronometrically-constrained four-variable analysis omitting quarry statues and the *HH* variable (head depth: head width). Century-by-century histograms of *moai* manufacture events for each of the remaining three analyses are presented in Figure 3.4. All three of the histograms may be rough approximations of a normal distribution over time. However, the first two demonstrate a mean, median, and maximum value in the fourteenth century while the mean, median, and maximum value of the third histogram are all in the fifteenth century.

The fact that the mean values for statue construction dates in analyses #5 and #6 (the chronometrically-constrained three- and four-variable analyses omitting quarry statues) are so close to the middle of the time range raises some concern. Although this pattern may be a feasible one for the island's prehistory, it also may reflect the pattern expected if all seriations involved in the analyses were dating statues randomly between AD 1000 and 1700. Considering that the collection of statue construction events could take the form of any imaginable distribution across the timeline, the tendency toward a normal distribution centered on or near the midpoint of the timeline (1350), is hard to dismiss as coincidence. Furthermore, this is a similar pattern to that demonstrated in the analyses containing quarry statues (analyses 2, 4, and 7). Although five out of the six analyses demonstrating normal distributions of statue manufacture events with a mean value close to 1350 (analyses 2, 4, 5, 6, and 7) have some degree of similarity (see Table 3.13), they also contain noticeable differences. These differences between the chronologies are enough to generate some skepticism as to their extreme similarity in terms of distribution of statue construction events over time.

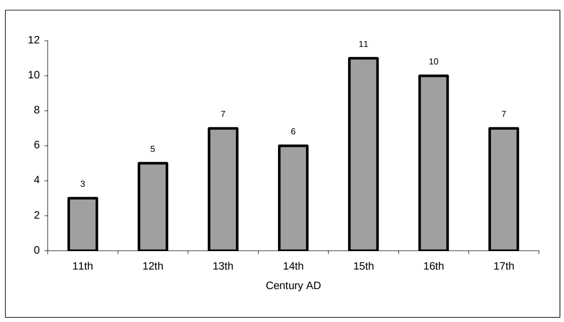
A formal statistical analysis is developed to test the possibility that the distribution of *moai* manufacture events in our remaining three chronologies (Analyses 5, 6, and 8) could be generated if seriation results were random. Each seriation analysis



(a)



(b)



(c)

Figure 3.4. Each figure plots the number of statues constructed by century. (a) refers to Analysis #5; (b) refers to Analysis #6; (c) refers to Analysis #8.

actually derives an average date value for each statue based upon one or many individual seriations in which that particular statue may appear (some statues appear in few or only one seriation if data for some variables is absent). The Central Limit Theorem of probability theory suggests that the sum of a large number of independent observations from the same distribution has, under certain general conditions, an approximately normal distribution. That is to say, if the observations (each date for an individual statue within the overall analysis) are drawn from the same distribution (for example, if a seriation analysis is assigning dates randomly rather than finding meaningful orderings), then our average dates for statues in the analysis would be expected to tend toward a normal distribution (limited by the small number of seriations considered).

To determine precisely what that expected normal distribution generated by random data would look like for parameters specific to each analysis under consideration, Analyses 5, 6, and 8 were repeated 30 times each, replacing seriation results with random dates for statues. This repeated testing presents an average value for the mean and standard deviation of the normal distribution generated by random dates. We can then use a traditional *Z*-test to determine the likelihood that each observed sample of statue construction events from Figure 3.4 is representative of the normal distribution expected in a random analysis. Respectively, the likelihood value for Analyses 5, 6, and 8 are 0.233, 0.054, and 0.035. If our null hypothesis is that our observed sample distributions from Analyses 5, 6, and 8 could be generated by seriations assigning random dates to statues, we fail to reject our hypothesis at the 95% confidence level for Analyses 5 and 6. However, the probability that Analysis #8, the chronometrically-constrained four-variable analysis omitting quarry statues and the *HH* feature, was generated by random seriations is extremely small. This test rejects the possibility (with 95% confidence) that the distribution displayed by the third histogram in Figure 3.4 could result from seriations randomly assigning dates to statues.

This does *not* indicate that Analyses 5 and 6 or any of the other analyses under consideration earlier in the chapter are random or that the OPS algorithm is assigning dates at random. As stated previously, the collection of statue construction events could take the form of any imaginable distribution across the timeline. Additionally, problematic data, radiocarbon dates, or even one individual feature may produce a small amount of noise or randomness such that the effect described in the Central Limit Theorem influences the final distribution of statue construction events in the analysis. However, subsequent derivations are based only on Analysis #8. Determining how accurate this statue chronology actually is in comparison to the others will require a tremendous amount of "ground-truthing" through creative chronometric analysis.

A Comparative Approach

The optimal statue chronology offered by Analysis #8 (Table 3.12) was derived and selected through a systematic and logical process. The results, along with the analysis, are likely to be challenged on the basis that archaeologists are not yet familiar with the OPS algorithm or *OptiPath* software. A more traditional technical approach to the idea of seriating *moai* may be occurrence seriation. Although a complete occurrence seriation analysis of the data is not offered here, the OPS algorithm and *OptiPath*

Table 3.15. An "X" indicates the statue has a variable value that is larger than average.

Name	Date	BW:TL	BD:BW	NM:MC	RE:EE	F:FL
05-080-01	1007		X	X	X	X
Nau Nau-01-01(R)	1051	X			X	
Nau Nau-01-10	1058				X	X
13-331-01	1142	X		X		
Nau Nau-01-02(R)	1148	X			X	
Road-NW-06	1152	X		X	X	
MTM-01	1166	X	X		X	X
Nau Nau-01-04(R)	1173	X			X	
14-463-02	1203			X	X	
New Ahu-01	1212	X			X	X
08-345-01	1227	X		X	X	
S-001-01	1229	X		X	X	X
08-003-02(R)	1245	X		X	X	
02-228-01	1282	X				X
Mata Ketu-01	1295	X	X	X	X	
New Ahu-03	1334	X	X	X		
Road-NW-10	1346					X
Road-NW-05	1377	X	X	X	X	
14-021-01	1388	X	X	X		
02-209-04	1397	X	X	X	X	
14-548-03(R)	1398	X	X		X	
14-548-07(R)	1407	X	X		X	
Road-I-06	1417	X	X	X		
03-077-01	1417			X		X
14-548-01(R)	1426	X				
07-584-09	1439		X	X		
14-548-08(R)	1439	X				
Akivi-01(R)	1467	X				
L-01	1471			X	X	X
13-478-01	1476	X	X			X
13-490-01	1495		X			X
14-021-03	1499	X	X			
12-220-01	1508	X		X	X	
12-323-01	1517		X			
14-548-06(R)	1526	X		X	X	
14-159-01	1553	X	X		X	
12-460-01	1554		X	X		
14-548-17	1580		X			
Tepeu-02	1581	X		X	X	
13-487-01	1581		X		X	
07-584-03	1590		X			
12-460-04	1598		X		X	
07-584-01	1607					
12-460-03	1611				X	
07-581-01	1625		X		X	
Tepeu-04	1628	X			X	
07-584-02	1648	X				
12-447-01	1674				X	
Nau Nau-01-03(R)	1700	X	X		X	

software can also organize the data using occurrence seriation as a special case of optimal path seriation.

As a means of interpreting the results of the optimal path seriation analysis in a manner more recognizable to those familiar with the traditional occurrence seriation technique, variable values can be divided into large or small, based on their size relative to the average variable value for statues. This *post hoc* dichotomization effectively breaks the data down into present/absent values (of a large feature value, for example).

Table 3.15 depicts a presence/absence table for large feature values based on the optimal chronology. Notice that variable *HH* (head depth: head width) is not included in the table as it was also excluded from the analysis. Results in Table 3.15 do not appear to represent a successful occurrence seriation. However, two factors may be contributing to "noise" in Table 3.15. First, some combinations of variable values are repeated from one statue to another at different points in the chronology. Aggregating statues that share combinations of feature values, a total of thirty groups are represented in the chronology. Twenty of these groups contain only one statue. Considering the span over which each group appears in the chronology rather than each individual *moai* manufacture event, groups with a single statue are removed from the chronology temporarily. Figure 3.5 displays the remaining ten groups and their chronological distributions.

Organizing these ten groups in rough chronological order (see Table 3.16), renders a pattern much more suggestive of a successful occurrence seriation. Part of the seeming disorder of Table 3.15 may be due to the fact that single-statue groups show no depth of time, and therefore their chronological representation may be incomplete.

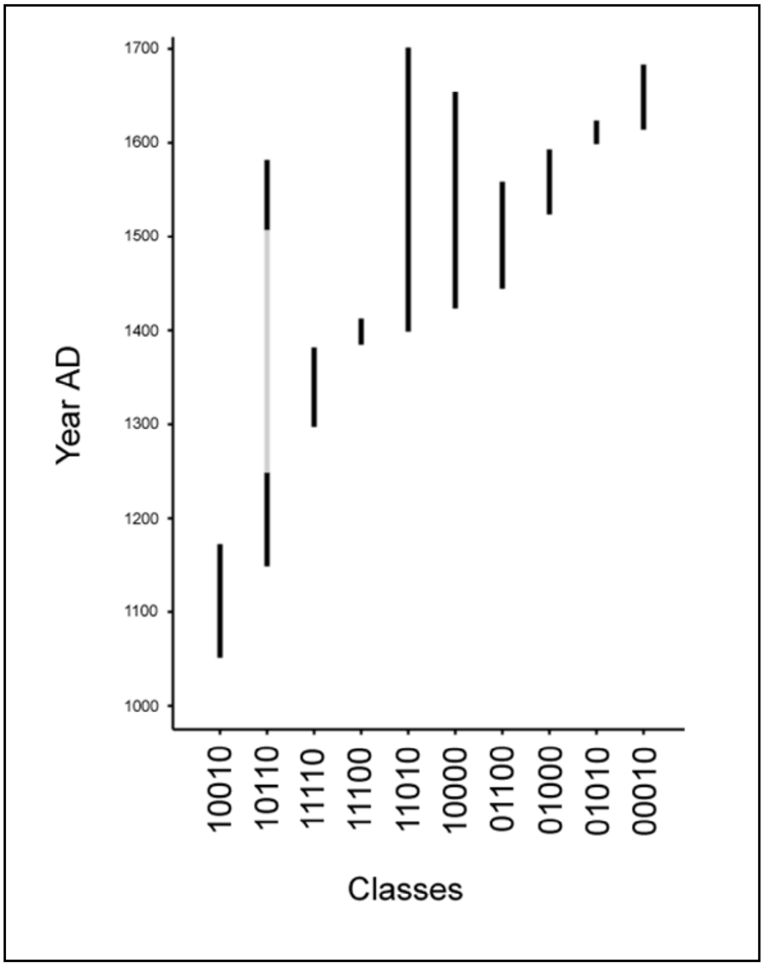


Figure 3.5. Chronological distribution of classes containing multiple statues. 1's and 0's refer respectively to X's and blanks in Table 3.14. Lightly shaded region indicates a long period of time in which no statues were constructed.

Regardless, Figure 3.5 and Table 3.16 may offer a more traditional interpretation to corroborate the optimal path seriation analysis and related statistical derivations.

At this point, the seriation analysis results may also be compared to generalizations of statue form made by Skjølsvold (1993) mentioned at the beginning of the chapter. Although Skjølsvold refers to the earliest statues as “naturalistically shaped”, a quantitative or metric equivalent is difficult to designate. Skjølsvold’s definition of natural may not be one that all archaeologists conform to. However, the “small, broad specimens” to which Skjølsvold refers may be reasonably represented through the *WL* variable used in the seriation analysis and the total length measurements initially collected for statues. By “broad” we might conjecture that Skjølsvold refers implicitly to a relatively high ratio of the width of the base to the total length of the statue, and by “small” he refers to statues that are relatively short. Seriation results suggests that there may have been a time span (roughly AD 1150 to 1300) for which the average base width value for statues was relatively high and the total length value for

Table 3.16. Chronological ordering of five-variable classes containing multiple statues. Note that the F:FL variable offers no additional information as all statues included have a relatively small ratio value for that variable.

Class	Statue Dates	BW:TL	BD:BW	NM:MC	RE:EE	F:FL
100010	1051, 1148, 1173	X			X	
100110	1152, 1227, 1245, 1508, 1581	X		X	X	
110110	1295, 1377	X	X	X	X	
110100	1388, 1417	X	X	X		
110010	1398, 1407, 1553, 1700	X	X		X	
100000	1426, 1439, 1467, 1648	X				
010100	1439, 1554		X	X		
010000	1517, 1580, 1590		X			
010010	1598, 1625		X		X	
000010	1611, 1674				X	

statues was relatively low. During this time period, the average *WL* (base width: total length) value was 0.49 (compared to 0.36 for all other time periods). The average total length for statues during the same 150 year span was 274 cm (compared to 495 cm for all other time periods).

The "tall, slim and well-developed statues" to which Skjølsvold refers at the end of the statue chronology, may be identifiable between approximately AD 1400 and 1700 in seriation results. In this case, we might assume that "slim" refers to a low ratio for the width of the base to the total length of the statue. During this time period, the average *WL* (base width: total length) value for statues was 0.36 (compared to 0.42 for all other time periods). The average total length for statues from this three hundred year span was 508 cm (compared to 374 cm for all other time periods). Much like Skjølsvold generalized, the seriation analysis presented here seems to identify a trend from short, squat statues to taller, slender statues over time. The metric approach to seriation may be a very useful means by which we can quantify and standardize our descriptions and understandings of trends in statue form over time. Furthermore, trends identified through seriation analyses of metric values for formal or morphological attributes may help to hypothesize about the ages of statues at different sites around the island (Figure 3.6).

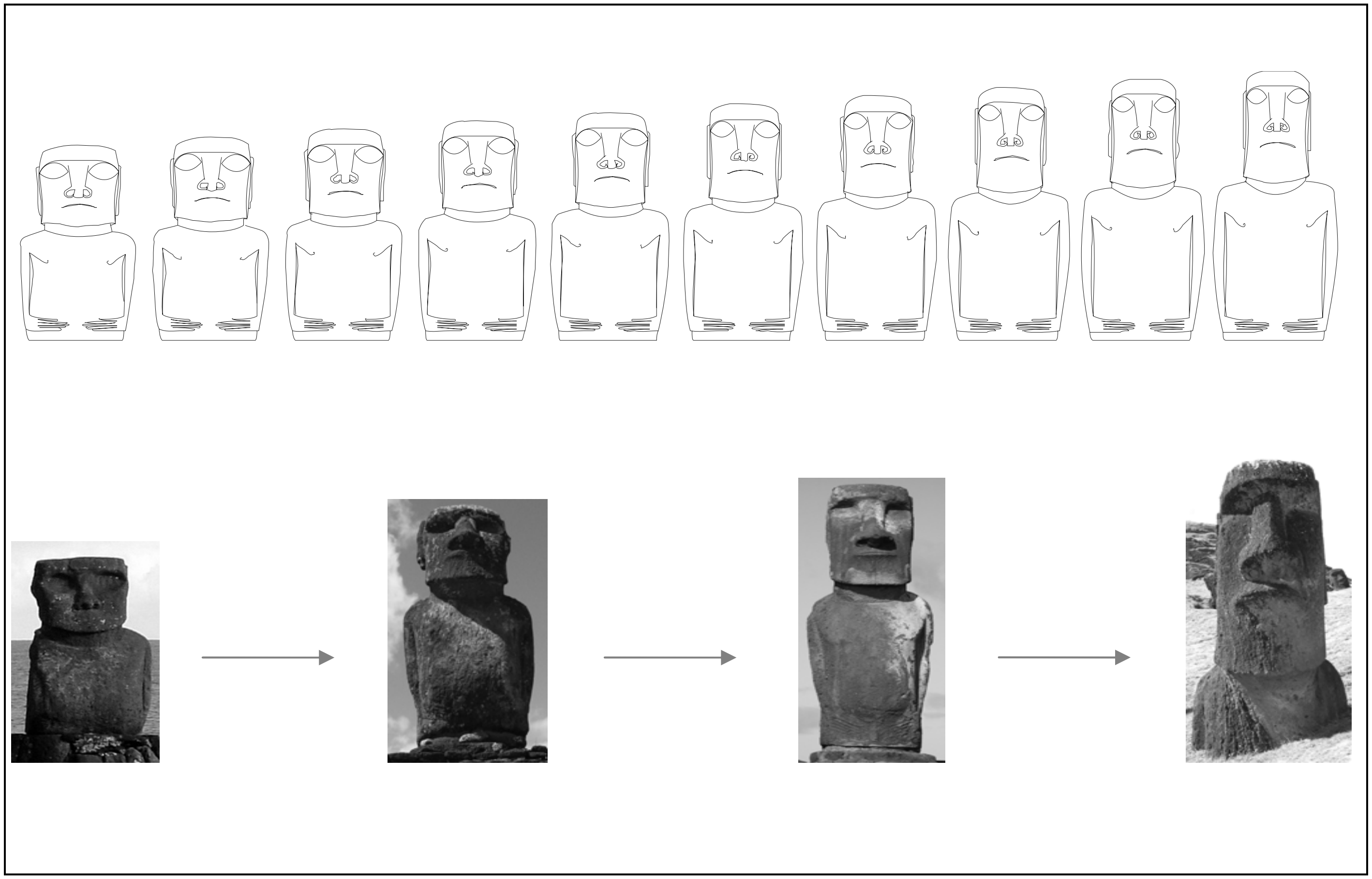


Figure 3.6. Schematic drawings for a gradual transition between statues with statistically average proportions from the first half and last half of the chronology from Analysis #8. Statues showing forms similar to schematic drawings from (left to right) Vai Uri, Akivi, Tongariki, and Rano Raraku.

Chapter 4. Estimating Energy Investment In Prehistoric Statuary

In other attempts to develop a chronology or even relative ordering of statuary, the goal was often rooted in an interest of the iconographic qualities of *moai* (Van Tilburg 1986). Here, contrastingly, the analysis of statue form or style is a means to investigate temporal and spatial patterns for prehistoric energy investment in the statue industry. Temporal and spatial trends in the formal or stylistic variation amongst statues may abound in the chronology developed here, yet a thorough discussion of these patterns is foregone in order to more completely explore the prehistoric evolution of energy investment in statuary.

Several recent studies in Rapa Nui (Hunt and Lipo 2001), elsewhere in Polynesia (Graves and Ladefoged 1995; Graves and Sweeney 1993) and even beyond (e.g., see Journal of Anthropological Archaeology, v18 n3) have begun to consider how energy investment in monumental architecture or statuary may be related to availability of natural resources, and in turn, how energy investment in monumental architecture in light of availability of natural resources may have impacted the relative success of human populations over time.

In developing a similar study aimed explicitly at the *moai* and Rapa Nui environment, work or energy is expressed in person-hours, or the amount of work that can be performed by an average worker in one hour. The general equation to calculate work throughout the following analysis is:

$$W = work = k_C 7v^{(2/3)} + k_R v + k_T x_T v + k_E v \qquad \text{(Equation 4.1)}$$

Some of the constants for this equation are based on previous research, and others are simply estimated in a rough manner. Although these estimates may lead to inaccurate absolute estimates of person-hours invested in statuary, they do provide important measures by which *relative* changes in work investment over time are apparent. In the equation above, k_C is a constant representing the person-hours per meter-squared required to carve the form (surface area) of a statue. For the current analysis, $k_C = 48$ person-hours per square-meter of surface area. The surface area, in turn, is estimated by $7v^{(2/3)}$. This estimate suggests that a statue's surface area (relative to its volume) is roughly equivalent to the surface area of a box whose dimensions are 1 unit x ½ unit x 2 units. Again, this estimate may significantly underestimate the surface area resulting from the detail of a statue's form, but it provides a standard by which relative comparisons between statues can be made.

The volume (v) of each statue was calculated as $w_b d_b l$ where, w_b is the width of the base, d_b is the depth of the base, and l is the total length of the statue. Although this measure for volume likely exceeds the actual volume for most statues, it was chosen for its simplicity and because it requires information available for a relatively high percentage of the statues. In other words, after deriving the statue chronology, subsequent estimates are made in a manner such that few statues are omitted from analysis due to a lack of information.

To continue, k_R is a constant representing the person hours per meter-cubed required to remove rubble from the carving area. The amount of rubble is estimated, in this case, to be equal to the total volume of the statue. For the current analysis, k_R = 5 person-hours per cubic-meter of rubble.

The remaining constants, k_T and k_E, refer to the transportation and erection of statues respectively. The transportation constant is a measure of person-hours per cubic-meter-kilometer. That is the person-hours required to transport one cubic-meter of statue exactly one-kilometer on a level surface. The forthcoming analysis sets k_T = 9.6 person-hours per cubic-meter-kilometer. The value for this constant was derived using archaeologist Charlie Love's (1990) transportation experiments in which 25 men transported a 10-ton concrete replica statue approximately 150 feet in two minutes. The 9.6 value is significantly higher than (roughly triple) Love's experimental value, taking into account a sustained work pace over a long period of time. Again, it may be important to iterate that estimates for the precise number of person hours required to move a statue a certain distance is not as important as being able to determine the different relative costs for moving different statues different distances.

Finally, a value of 80 person-hours per cubic-meter was used for the constant k_E. However, this constant was only applied to statues that reside in the context of an *ahu*. Although some statues that were not placed upon formal *ahu* structures may have at one time been erected (Heyerdahl et al. 1989; Routledge 1919), the process for erecting statues on *ahu* may have been a unique one, and considerably more energy-intensive. The only remaining variable in the work equation is x_T, the distance each *moai* was transported. There are several different ways in which the distance between the statue quarry and a statue's final resting point may be measured. The simplest estimate may be a straight line, yet this fails to account for the island's topography. Ideally, research on *moai* transport routes would yield extensive maps across the islands by which more precise estimates could be made. However, even with thorough maps of *moai* roads, it may be impossible to determine which *moai* were transported along which specific roads.

To account for the island's varied topography and to allow for some ingenuity in the prehistoric statue industry, transport distance in this model was calculated based on a least-cost route, in turn calculated based on a cost-surface analysis of the terrain traversed. Cost-surface analyses emerged in archaeological analyses nearly twenty years ago (e.g., Limp 1989) and were initially an outgrowth of site-catchment analyses of optimal foraging models (see van Leusen 2002). Cost-surface analyses generate a system of weights to describe the characteristics of terrain (e.g., slope, land cover, natural or manmade barriers) that may influence the costs associated with traversing specific geographic regions (Kvamme 1999).

In order to determine the cost of the least-cost route from the Rano Raraku statue quarry to each individual statue, several steps were taken. Using ArcGIS, a contour map of the entire island (10m intervals) was converted to a triangulated irregular network (TIN). The TIN was then used to interpolate elevations between contour intervals and create a digital elevation model (DEM), in which the island is divided into 300m x 300m quadrats—each attributed with an average elevation value (Figure 4.1). While GIS technology and software may allow for a much more detailed DEM, a relatively low resolution is employed so that geographic analyses in this chapter do not lead to overwhelming

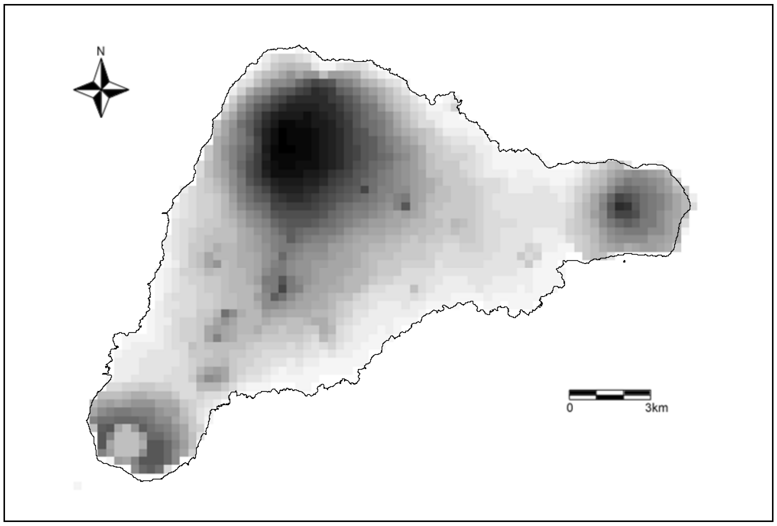


Figure 4.1. Digital elevation model of Rapa Nui. Each quadrat is 300m x 300m. Darker areas indicated higher elevations.

computing requirements for the computer simulation developed in the next chapter. Slope values were calculated for each 10 meter by 10 meter zone, and eventually an average slope value was assigned to each 300 meter by 300 meter quadrat (Figure 4.2). ArcGIS is then used to calculate the least possible cost to travel from the Rano Raraku statue quarry to each quadrat on the map. The cost to traverse each quadrat is calculated based on the distance multiplied by the average slope value for the quadrat (Figure 4.3). This is a simplistic cost-surface analysis, but generates a system of relative transport costs for statuary, which is all that is required for estimating the relative amounts of energy invested in each statue.

Each individual statue is then assigned an x_T value (cost-distance from the statue quarry) according to the quadrat in which it resides. One problem with the least-cost approach to the distance measure is that there is little archaeological evidence to demonstrate that the prehistoric statue industry actually transported statues along such

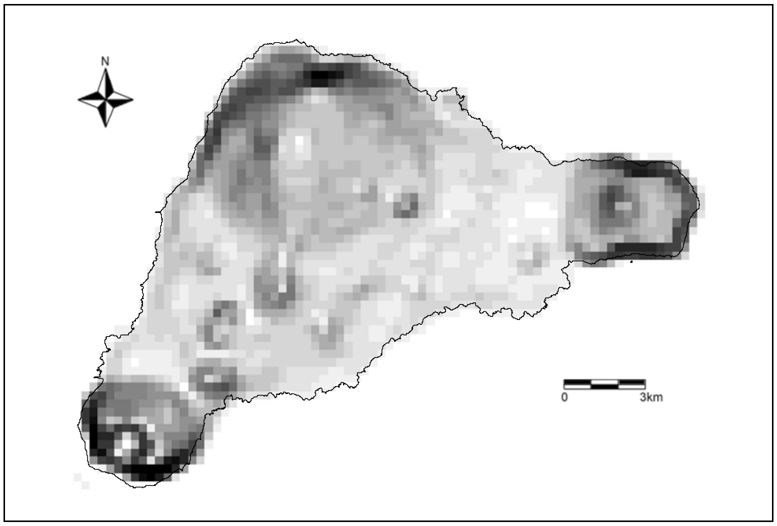


Figure 4.2. Slope raster for Rapa Nui. Each quadrat is 300 m x 300 m. Darker areas indicate steeper slopes.

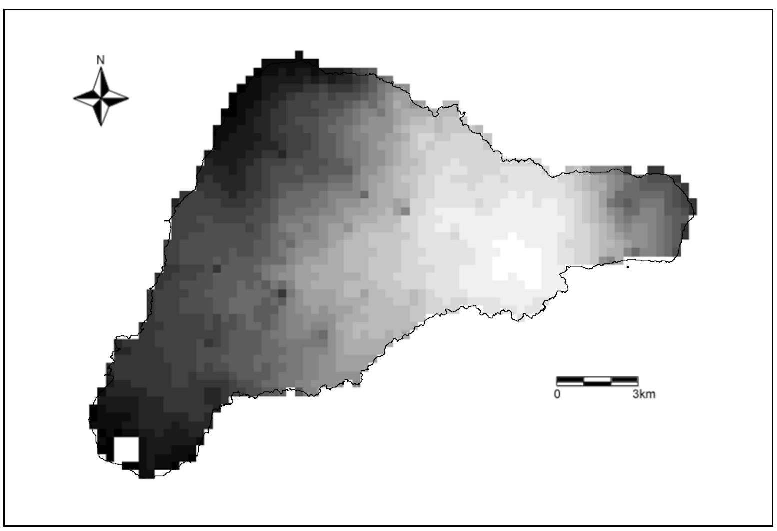


Figure 4.3. Cost-distance raster for Rapa Nui. Each quadrangle is 300 m x 300 m. Darker areas indicate greater costs associated with transporting statues from the Rano Raraku quarry.

efficient routes. However, considering that islanders were transporting enormous megaliths for multiple centuries, it is not hard to imagine that they would have streamlined the process in whatever way possible. A second problem with the least-cost approach is that, in this case, the slope value of the terrain incurs an equal cost whether the statue is being transported up the slope or down the slope. Without knowing the precise direction of travel, however, there is considerable difficulty in making the cost-raster a directional one. Additionally, there may be some justification for high costs when traveling down a slope. Keeping a multi-ton statue under control on a downhill, or preparing any rigging for braking purposes, may have been time- or energy-intensive.

Also of some concern are those three statues in the chronology that were not carved from Rano Raraku tuff (*02-228-01*, *MTM-01*, and *S-001-01*). All three of these statues are carved from parent material abundant in the immediate area of the statue, and therefore no transportation costs are calculated. In general, the equation used to calculate energy or work investment in statuary may not be ideal in terms of absolute accuracy, yet major energy sinks associated with the carving, transport, and erection of each individual statue are included. Furthermore, this study is not particularly concerned with the actual number of person-hours invested in the *moai* industry but rather with the variability of person-hours invested in statuary over both time and space on the island. This approach assumes that any changes in methods or technology in the statue industry over time did not significantly change constant values in the equation from one statue to the next.

An Island-wide Analysis of Energy Investment in Statuary

In analyzing the variability of energy investment in statuary over time and space in Rapa Nui prehistory, there are a number of potential scales of analysis that may or may not be appropriate. Throughout the forthcoming analyses energy investment is quantified by century. This scale is used as an intuitive one and one that makes the study compatible with previous published analyses of monumental architecture on Rapa Nui (Martinsson-Wallin 1994). Any smaller temporal unit may be inappropriate considering that the average standard deviation for statue dates in the chronological analysis is 95.4 years (see Table 3.11).

In terms of spatial scale, the analysis begins by interpreting the entire island as a single geographical unit. Martinsson-Wallin (1994) also considered the entire island as a single geographical unit in a century-by-century comparative analysis between the number of calibrated ^{14}C dates for settlement (habitation) sites and the number of calibrated ^{14}C dates for *ahu* documented for the island. Figure 4.4 displays an adaptation from Martinsson-Wallin's work (1994:81, Fig. 53a). There appears to be some correlation ($R^2 = 0.6$) between the abundance of ^{14}C dates for settlement sites and *ahu* on the island. This correlation may reflect a trend of the number of ceremonial *ahu* sites increasing (or decreasing) as the number of settlement sites and perhaps population increases (or decreases).

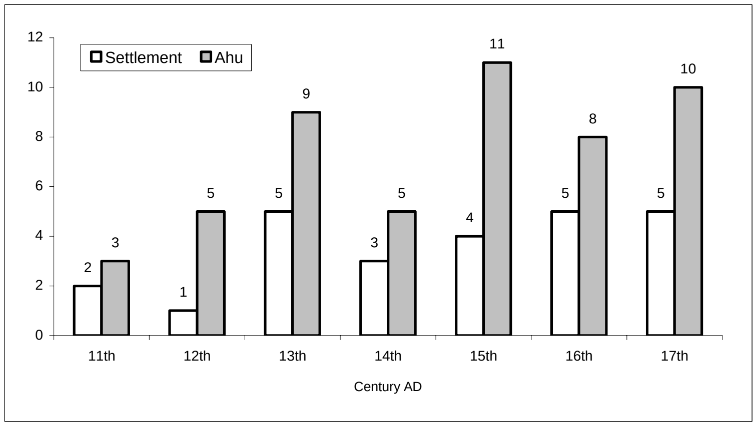


Figure 4.4. Adaptation of Martinsson-Wallin (1994:Fig 53a) comparing the number of radiocarbon dates for settlement sites and *ahu* by century.

There may be little surprise to see in Figure 4.5 that the number of dates for *moai* from the OPS analysis also shows some correlation (R^2 = 0.45) with the number of ^{14}C dates for settlement sites. Statues, like *ahu*, were ceremonial constructions, and like *ahu*, construction of statues may have intensified (or subsided) based on the growth (or decline) of settlements or population size on the island.

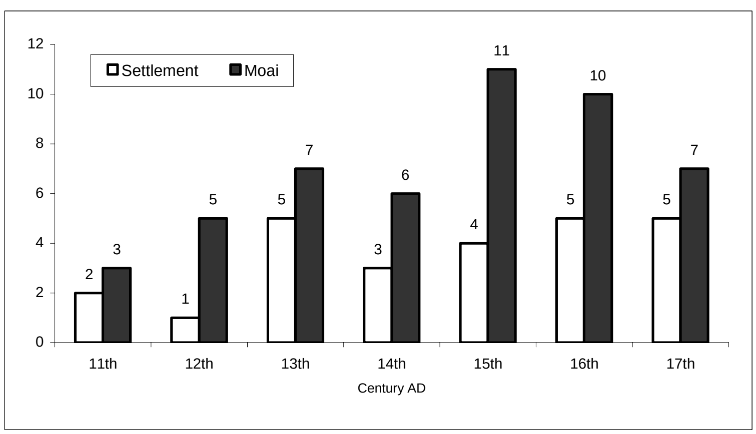


Figure 4.5. Comparison of the number of radiocarbon dates for settlement sites (Martinsson-Wallin 1994) and the number of statue dates from OPS analysis for each century.

Additionally, Figure 4.6 demonstrates an even stronger correlation (R^2 = 0.68) between the number of ^{14}C dates from *ahu* and the number of dates for *moai* from the OPS analysis. Recall from seriation analyses, twenty-four out of forty-nine statues included in the final chronology were bound by chronometric dates from *ahu*. These dates may account for part, but not all, of the correlation between statues dates and *ahu* dates. Except for the discrepancy in the 17th century, where the number of *ahu* dates increases from the previous century and the number of *moai* dates decreases, *ahu* and *moai* show extremely similar trajectories for their abundance in dating analyses in Figure 4.6. Martinsson-Wallin (1994:73) suggests that although the, "size of the *ahu* has

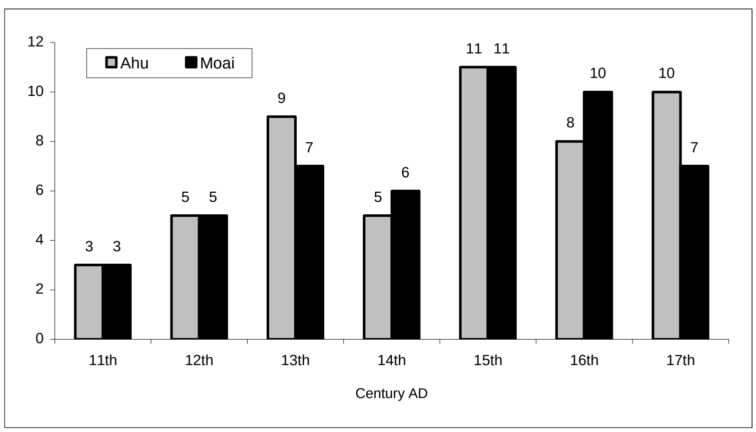


Figure 4.6. Comparison of the number of radiocarbon dates for *ahu* (Martinsson-Wallin 1994) and the number of statue dates from OPS analysis for each century.

changed from large, to medium, to small," *ahu* construction may have continued all the way through the 18th century. Martinsson-Wallin (1994:72) also states that, "A clear trend is however that late structures have few or no statues." While the late difference in numbers between *ahu* and *moai* in Figure 4.6 may be due to sampling error, it may also reflect a change in ceremonial site composition on the island.

The correlations between the number of statues constructed per century and the number of settlement and/or *ahu* dates suggests that the number of statues increased (or decreased) proportionately with the increase (or decrease) of both population and *ahu* on the island. However, the number of statues constructed may have little bearing on the energy or work investment in statuary. Overall statue size, in terms of volume, changed throughout the chronology (see Figure 4.7), as did the destinations for completed statues. Both of these factors may lead to some disproportion between the number of statues constructed per century and the amount of energy invested in statuary per century.

Figure 4.7. Statue volume (*base width x base depth x total statue length*) plotted over time.

Table 4.1 lists the statues included in the chronology, the dates assigned to the construction of each statue, the estimated energy investment for each statue, and a total sum of energy investment for each century. For some centuries in the analysis, certain statues do not have sufficient data to provide energy estimates. In these cases, the statues are assigned an average energy value based on other statues constructed and transported

Table 4.1. Chronology and work estimates for statuary based on OPS analysis.

Name	Date	Work	100-year Sum (work)	
05-080-01	1007	4935.65	7456	1000-1100
Nau Nau-01-01(R)	1051	1029.12		
Nau Nau-01-10	1058	1491.18		
13-331-01	1142	1074.94	4795	1100-1200
Nau Nau-01-02(R)	1148	1080.99		
Road-NW-06	1152			
MTM-01	1166	611.63		
Nau Nau-01-04(R)	1173	1068.41		
14-463-02	1203	1194.47	14599	1200-1300
New Ahu-01	1212	426.62		
08-345-01	1227	4740.32		
S-001-01	1229	334.00		
08-003-02(R)	1245	4844.41		
02-228-01	1282			
Mata Ketu-01	1295	973.47		
New Ahu-03	1334	2401.49	18798	1300-1400
Road-NW-10	1346	3956.76		
Road-NW-05	1377	820.37		
14-021-01	1388	1612.39		
02-209-04	1397	4588.47		
14-548-03(R)	1398	5418.95		
14-548-07(R)	1407	4297.42	43231	1400-1500
Road-I-06	1417	2938.81		
03-077-01	1417	5125.62		
14-548-01(R)	1426	5994.61		
07-584-09	1439	1170.59		
14-548-08(R)	1439	4982.86		
Akivi-01(R)	1467	2634.23		
L-01	1471			
13-478-01	1476	3151.72		
13-490-01	1495	4170.83		
14-021-03	1499	4834.32		
12-220-01	1508	5407.16	30291	1500-1600
12-323-01	1517	3084.82		
14-548-06(R)	1526	4657.49		
14-159-01	1553	450.28		
12-460-01	1554	3761.43		
14-548-17	1580	4567.42		
Tepeu-02	1581	1053.16		
13-487-01	1581	2077.87		
07-584-03	1590	4205.42		
12-460-04	1598	1025.68		
07-584-01	1607		15820	1600-1700
12-460-03	1611	1705.10		
07-581-01	1625	3865.51		
Tepeu-04	1628	907.22		
07-584-02	1648	5256.82		
12-447-01	1674	490.12		
Nau Nau-01-03(R)	1700	1335.54		

within the same century. Figure 4.8 displays the calculated century-by-century trajectory for energy investment in statuary. As with the histogram for statue construction events by century in Figure 3.3, the energy investment figure suggests that for the island as a whole, the statue industry may have intensified gradually between the 11th and 14th century. Then energy investment grows to a peak sometime in the 15th century, and subsequently declines rapidly toward the end of the chronology.

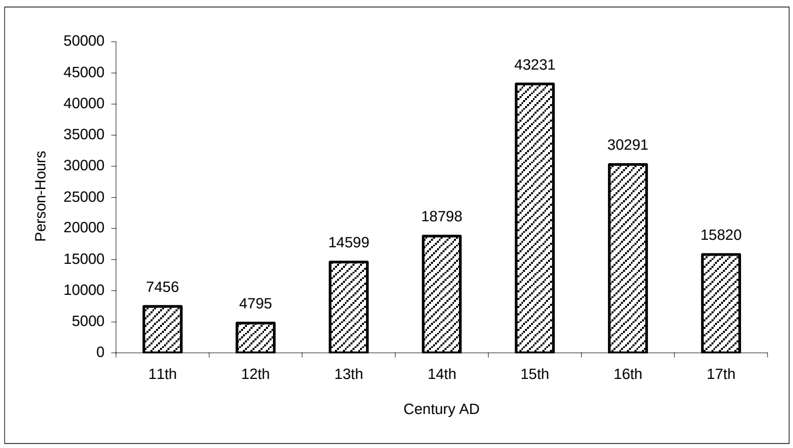


Figure 4.8. Estimates for energy investment in statuary by century, based on OPS analysis.

If Martinsson-Wallin's (1994) analysis of settlement dates is considered to be a proxy for population for the island, then energy investment in statuary shows much less correlation ($R^2 = 0.27$) to population size than the number of statues constructed does. Finally, a comparison is drawn between the number of statues constructed each century and the energy investment in statuary each century (Figure 4.9). In this case there appears to be a high correlation between the two ($R^2 = 0.85$). All of these patterns may be significant, yet they are difficult to explain at such a broad level of

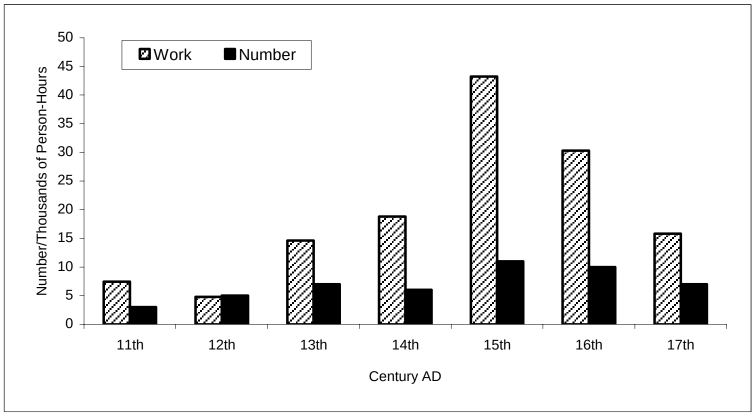


Figure 4.9. Comparison of the number of statues constructed each century and energy invested according to OPS analysis.

geographical interpretation. To summarize potentially interesting or important points that may be drawn from the island-wide analysis of statue construction and work investment in statuary:

1) Both the number of statues and the amount of energy invested in statuary appear to peak in the 15th century and decline thereafter. This pattern is also reflected in Martinsson-Wallin's (1994) analysis of *ahu* construction.
2) The number of statues constructed each century may be correlated with the population size (or at least number of settlements), but energy investment in statuary does not show the same correlation.

Both of these points may be explained, or at least more fully-investigated, with a more detailed geographical approach, and in a subsequent chapter, with reference to temporal-spatial variability in island resources.

Estimating Energy Investment in Statuary – Territorial Divisions

Several different historic geographical divisions have been identified for Rapa Nui, reflecting either boundaries recorded in ethnohistoric studies or boundaries based on analyses of variability in archaeological remains (e.g., Furgeson and Gill 2005; Hotus et al. 1988; Kirch 1984; Métraux 1940; Routledge 1919; Shepardson 2005a; Stevenson 2002). The different geographic divisions can be sorted into two general forms, although variation exists within forms as well. There are those divisions that are based on the tribal territories recorded ethnohistorically by Routledge during her fieldwork from 1914 to 1915, and there are those divisions that are more closely related with a traditional Polynesian *ahupua'a* scheme.

The tribal and *ahupua'a* divisions might both help to offer significant interpretations of spatial variability for energy investment in prehistoric statuary on the island. And it is possible that both territorial schemes played important historical roles on the island for distinct periods of time. While energy investment in statuary is considered very briefly for each of these two geographic divisions of space, the majority of the dissertation relies on a simple north/south division to examine spatial variability.

Perhaps the oldest proposed geographical sub-divisions for Rapa Nui were those recorded by Routledge (1919) and described in detail by Métraux (1940). Figure 4.10 displays the divisions described by Routledge and Métraux. These territorial divisions have provided the foundation for several spatial analyses on the island (e.g., Lee 1986; Martinsson-Wallin 1994; McCoy 1979; Rounds-Beardsley 1990) and were subsequently georectified based on inland statue locations (Shepardson 2005a).

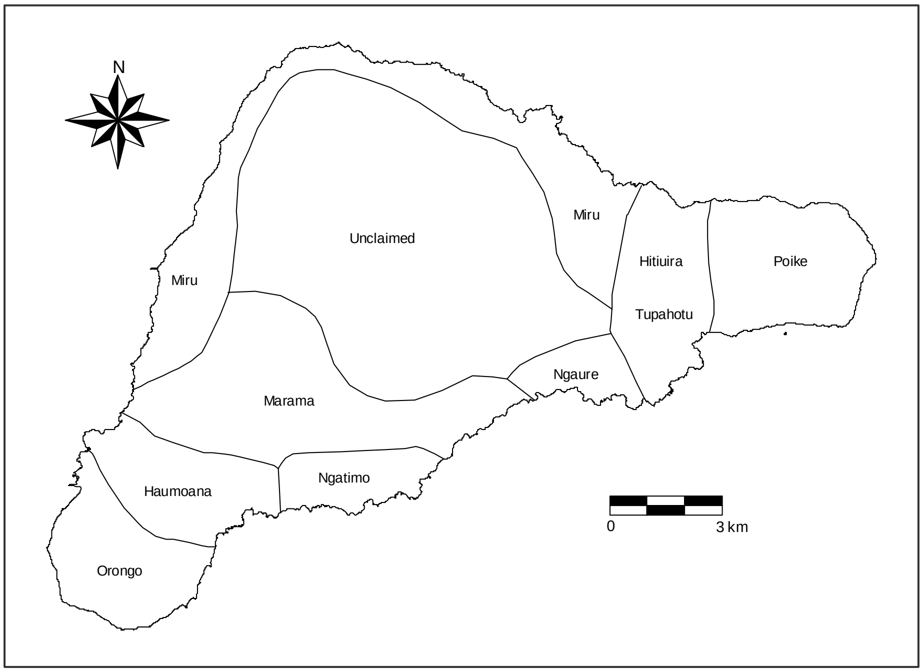


Figure 4.10. Territorial divisions originally drawn by Routledge (1919) and revised by Shepardson (2005a).

Routledge suggested that the divisions between tribes (or *mata*) were familial ones, relating to the lineages of the sons of the island's legendary founder, Hotu Matua. According to oral tradition, Rapa Nui was divided into districts for six sons of Hotu Matua: Tu‘u-ma-heke, Miru, Marama, Ra‘a, Koro-orongo, and Hotu-iti (Métraux 1940; Routledge 1919). Métraux (1940:122) made the interesting observation early on that:

> Supposing the traditional land division to be accurate, there would remain five groups (Haumoana, Ngatimo, Ngaure, Tupa-hotu, and Hitiuira) whose origin cannot be attributed with certainty to any known ancestor or to any ancestor whose name can be placed on a genealogical record. A logical supposition is that the curious absence of a definite district associated with the names of Hitiuira and Tupa-hotu indicates that these tribes have developed since the other groups to whom special territory was allotted. The

greater importance of Marama in comparison with Ngatimo and Huamoana tends to indicate that the latter were originally subtribes of that important *mata*.

Thus, the divisions mapped by Routledge appear to reflect a combination of the previously established territories and the integration or subdivisions that may have taken place afterwards. Furthermore, Métraux (1940) also suggests that each of the *mata* may have had internal distinctions based on separate lineages. Ultimately, while precise geographic divisions of the island may offer a useful heuristic for spatial analyses, the transient nature of social divisions on the island may add a degree of uncertainty to the significance of any spatial patterns in island-wide archaeological analyses.

In order to calculate the trajectory of statue production or energy investment in statuary for each individual territory over time, every statue in the seriation analysis was first attributed to the territory in which it now resides. For those statues suggested to reside directly on the boundaries between territories by Shepardson (2005a), statues were attributed to the territory which they would face if erected from their current positions. Figure 4.11a-f plot the histograms of numbers of statues constructed each century for each individual territory. The fact that the Ngaure *mata* is not represented by any statues in the analysis, and that four of the statues in the analysis pertain to a region that Routledge labels as "unclaimed" suggests that there may be sampling issues that are difficult to contend with when the spatial analysis includes a relatively large (nine) number of geographic divisions.

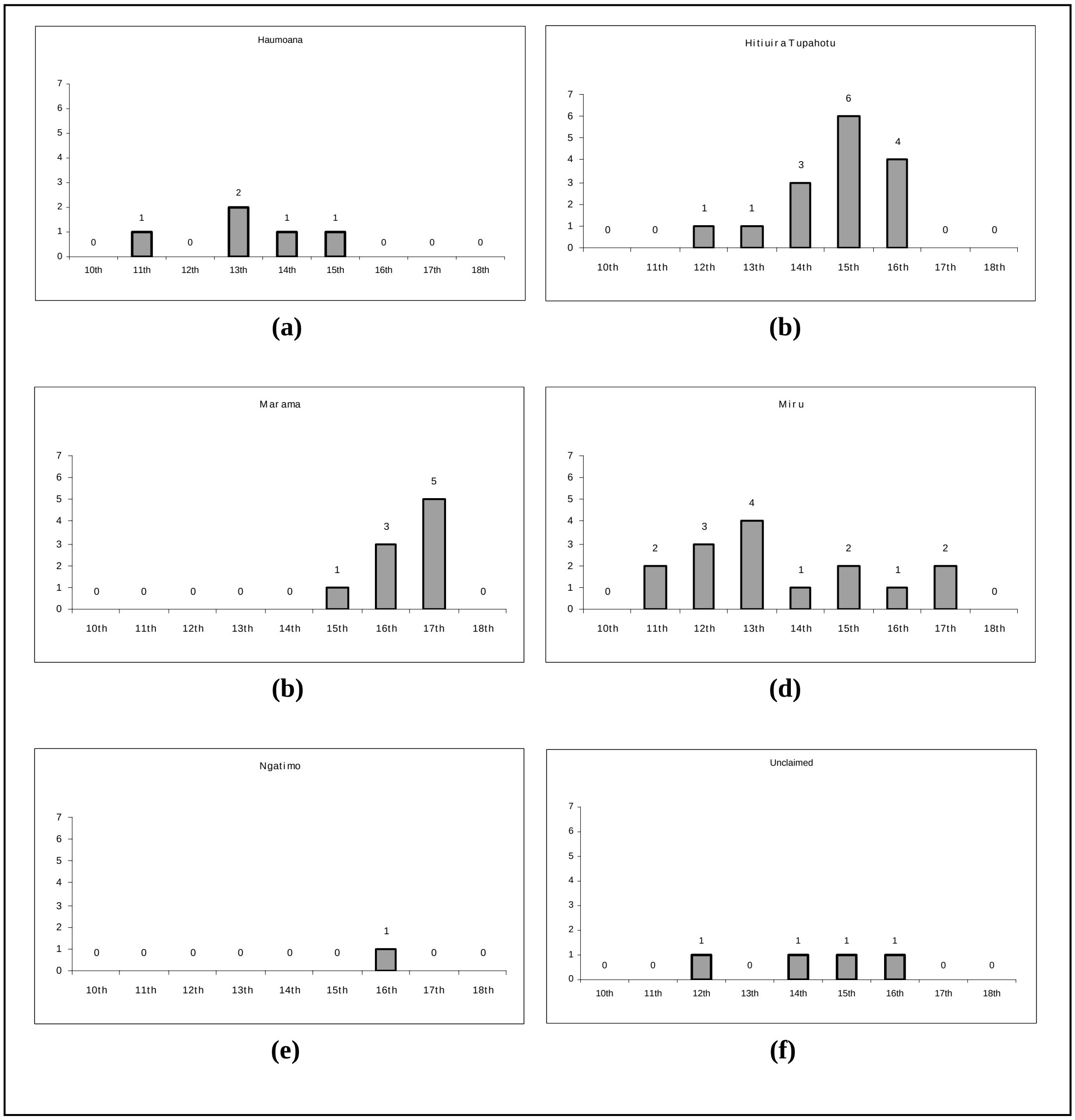


Figure 4.11. Number of statues contsructed by century (according to OPS analyis) for territories drawn by Routledge.

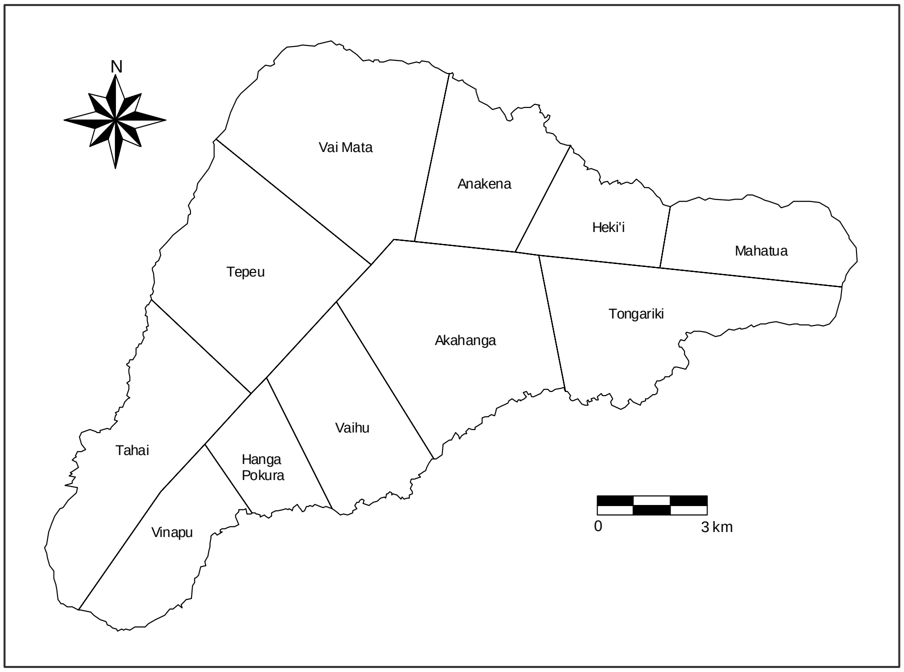


Figure 4.12. Territorial divisions as drawn by Stevenson (2002).

Another possible set of geographic sub-divisions for the island were proposed by Stevenson (2002). His statistical analysis of *ahu* styles and comparison to a traditional Hawaiian *ahupua*'*a* system of territorial divisions rendered a network of divisions radiating toward the coast from a central axis partitioning north from south on the island (see Figure 4.12). Although Stevenson does not cite Hotus et al., the similarities between the proposed territorial divisions is obvious (compare Figures 4.12 and 4.13). Interestingly, Hotus et al. appear to have determined territorial boundaries according to the locations of *pipi horeko* (stone cairns) around the island rather than *ahu*. McCall (1979) also believed that *mata* boundaries were delineated by *pipi horeko*. Routledge, on the other hand, stated in her unpublished notes that she was under the impression that *pipi horeko* did not indicate boundary lines but rather acted as *tapu* markers and/or

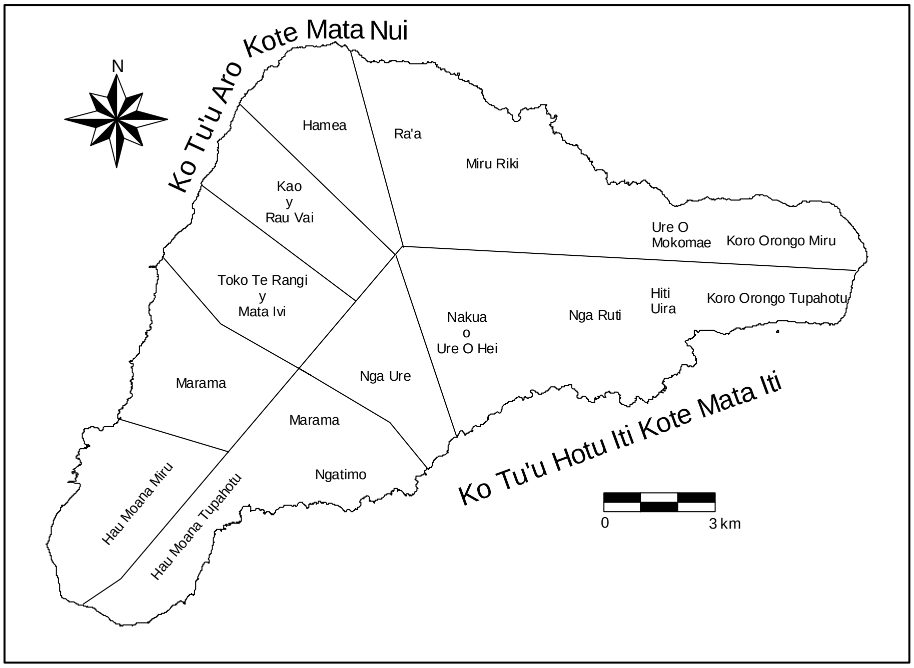


Figure 4.13. Territorial divisions proposed by Hotus et al. (1988).

monuments for the deceased. The divisions proposed by Stevenson, and their similarities or relations to those published by Hotus et al. and Routledge are intriguing and deserve further investigation in the future. Figures 4.14a-h plot the histograms for numbers of statues constructed each century based on Stevenson's territorial map.

Part of the problem with the spatial analysis of statuary using either Routledge's or Stevenson's territorial divisions is that the results are somewhat cumbersome, and the sample size for each individual territory is relatively small. Simultaneously comparing energy estimates from nine or eleven geographical regions is difficult, and the small sample sizes yield results that may not allow for adequate confidence. Any interpretation of these results would be mostly speculative.

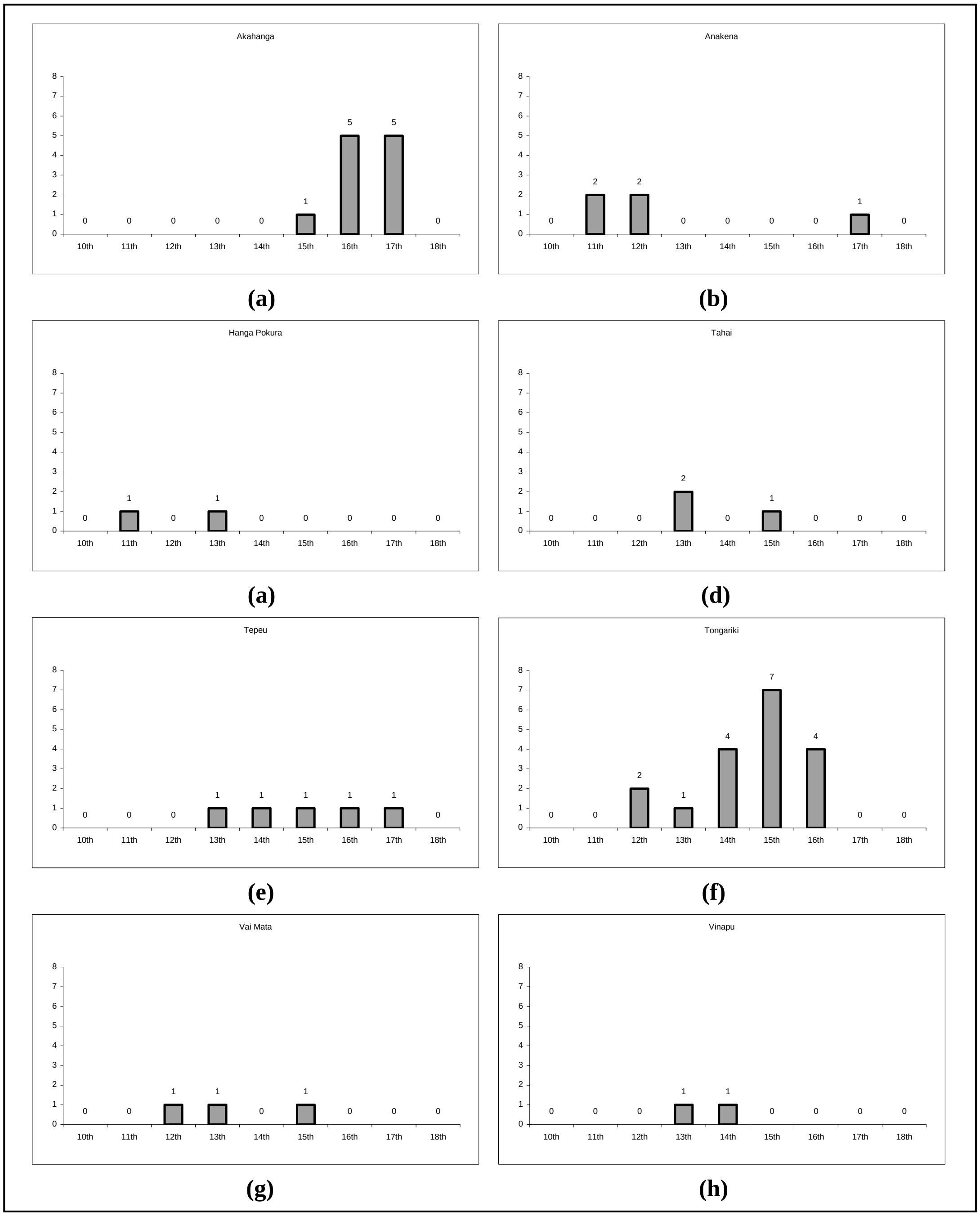


Figure 4.14. Number of statues constucted by century (according to OPS analysis) for territories drawn by Stevenson.

Estimating Energy Investment in Statuary – North vs. South

Throughout this dissertation, estimates for energy investment in statuary, along with significant differences in ecological and social conditions, are calculated for the northern region and southern region of the island. The dividing line between the two regions, in this case, is the same axis as defined by Stevenson's work (Figure 4.15), and nearly identical to that included by Hotus et al. (1988).

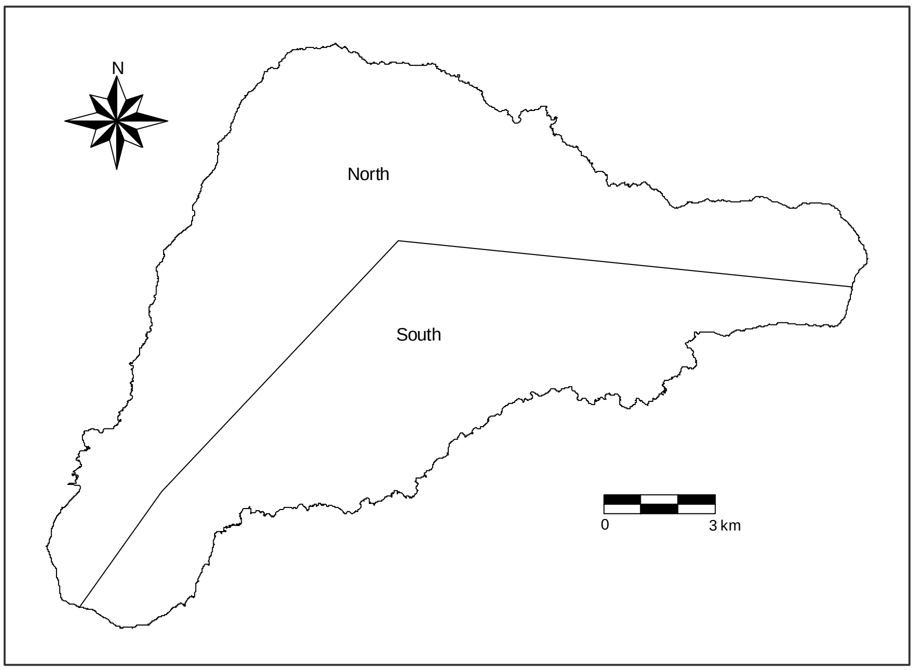


Figure 4.15. Rapa Nui divided into northern and southern regions.

The north/south division is selected as the foundation for spatial analyses partly to reduce the complexity of the analysis from nine or eleven geographic regions to just two, but also because it may help to account for spatial variability attributable to Stevenson's or Hotus et al.'s *ahupua'a* territorial scheme as well as Routledge's *mata* territorial scheme (see below). Furthermore, some researchers have attempted to draw a distinction between the northern and southern regions based on natural climatic or environmental factors. Graves and Sweeney (1993) imply the north/south distinction to reflect rainfall variability between the windward and leeward regions of the island, and McCall (1979), citing a report by the Chilean Office of National Planning (ODEPLAN 1972), suggests that the most productive soils on the island are found primarily along the northern coast of the island. Conjectures regarding the relationship between climatic or geological variability and the north/south distinction have not yet been thoroughly substantiated. However, there is still considerable evidence for a north/south social division on the island, mostly stemming from oral traditions and archaeological remains.

Stevenson's (2002) work provided an explicit rendering of the location of the north/south division for the island. Earlier work referred to a similar boundary on the island without an actual mapped location (e.g., McCall 1979; Métraux 1940; Routledge 1919). However, prior to Stevenson's work, discussions appear to have categorized this boundary as an east/west division rather than north/south. Regardless, in all cases the division refers to a distinction between two large historic sociopolitical groups on the island described to ethnohistorians and referred to in oral traditions: the Ko Tu'u in the northwest and the Hotu Iti in the southeast. These groups have also been referred to as *mata nui* (greater groups) and *mata iti* (lesser groups) respectively (Métraux 1940). Overlaying Stevenson's north/south division on Routledge's original territorial map of sociopolitical boundaries on the island demonstrates the dividing line to be a plausible approximation for the geographic separation between the Ko Tu'u and Hotu Iti (Figure 4.16). However, Stevenson's north/south axis does appear to bisect the Hitiuira and

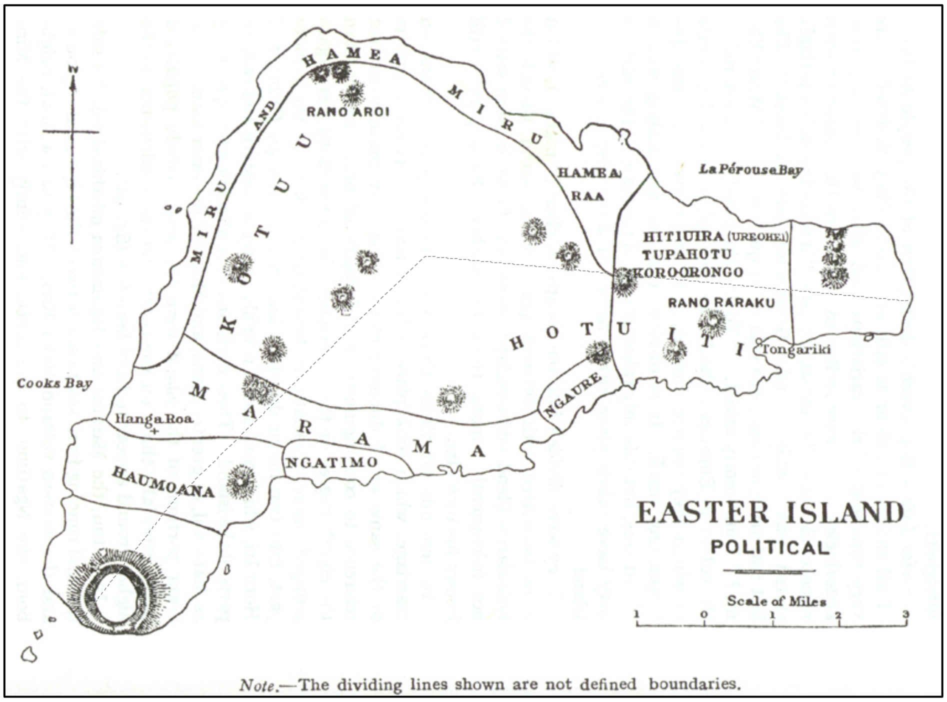


Figure 4.16. Stevenson's (2002) north/south axis (grey dashed) overlayed on Routledge's (1919) political map of the island.

Tupahotu *mata*, whereas earlier accounts suggested that clans in that area all pertained to the southeasterly Hotu Iti moiety. The same might be said for the southwestern region where the north/south axis bisects the Haumoana *mata*.

Again, these details reiterate that the two-part division of the island is meant only as a rough estimate for significant geographic variability discussed in this dissertation. Additional archaeological research devoted entirely to the study of territoriality will be required to solidify the spatial locations and temporal duration of social boundaries.

The division between the Ko Tu'u and Hotu Iti, according to Métraux (1940), reflects regional integration amongst smaller *mata* on the island. And McCoy (1979) posits that such integration may have resulted from intertribal warfare or conflict. However, while conflict between smaller *mata* may have led to integration, oral traditions describing conflict between the larger Ko Tu‘u and Hotu Iti groups intimate that the rivalry may have perpetuated, rather than dissolved, a geographical social boundary.

As McCoy (1979:144) suggests of the battles between the Ko Tu‘u and Hotu Iti:

> From the descriptions of burning, looting, killing and taking of slaves it is clear that warfare was intended to force withdrawal from the land, thereby leaving it for exploitation by the victorious party.

While the exact boundary between the two alliances may not have been static, the volatile and adversarial relations between the moieties may have reduced the permeability of the social boundary, or at least changed islanders' dispositions toward the prospect of entering enemy territory. As simulation efforts in Chapters 5 and 6 reveal, the issue of permeability for the boundary between the northwestern and southeastern territories may be an important one. Without restricting islander mobility from one territory to another, simulation results imply that there might be little reason to expect spatial variability in environmental pressure or culture historical trends on the island.

Before proceeding, the possibility that the north/south social boundary affected cultural transmission or produced obvious differential trends in chronological variation of statue form is briefly considered. Parameters from seriation Analysis #8 from Chapter 3 were applied to statues that reside in the northern region of the island and statues that reside in the southern region of the island separately. If the north/south distinction were a variable that affected cultural transmission of statue aesthetics, seriation results (in terms of the average standard deviation of dates assigned to individual statues over a suite of five seriations) might be expected to improve when spatial variability is controlled.

However, when seriating statues from the north and south separately, results worsen in both regions. The average error (standard deviation) per statue increases from 95.4 years (Analysis #8, Chapter 3) to 210.8 years for the north. The average error (standard deviation) per statue increases from 95.4 years to 96.2 years for the south. These results might be interpreted to imply that the north/south geographic distinction did not significantly affect transmission process of statue form. However, it is also important to realize that the results may be related to the size or chronological representativeness of the samples selected for analysis. Only sixteen statues were available for analysis in the northern region, and only thirty-three were selected for the south.

Figures 4.17a-b plot the numbers of statues constructed each century for the northern and southern regions of the island. The histogram for the number of statues constructed during each century within the northern region is particularly striking for its smooth increase to a peak in the 16th century and rapid falloff. When compared to data calculated by Stevenson (1997) for southern settlement sites, a clear correlation is apparent ($R^2 = 0.82$, see Figure 4.18). According to Stevenson (personal communication), the settlement data may be indicative of the population trajectory for the area. Calculations for energy investment in statuary for the southern region also show, albeit smaller, a correlation with Stevenson's settlement data ($R^2 = 0.55$). Clearly settlement data, as well as statue data is limited both regionally and in numbers. Analogous settlement data for the north coast of the island is not yet available. As more data becomes available, it will be important to reassess correlations.

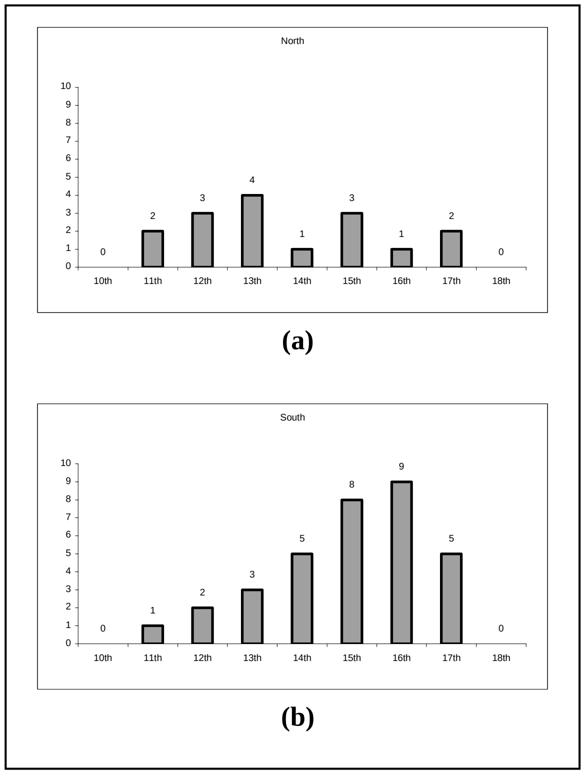


Figure 4.17. Number of statues constructed by century (according to OPS analysis) for northern and southern regions of Rapa Nui.

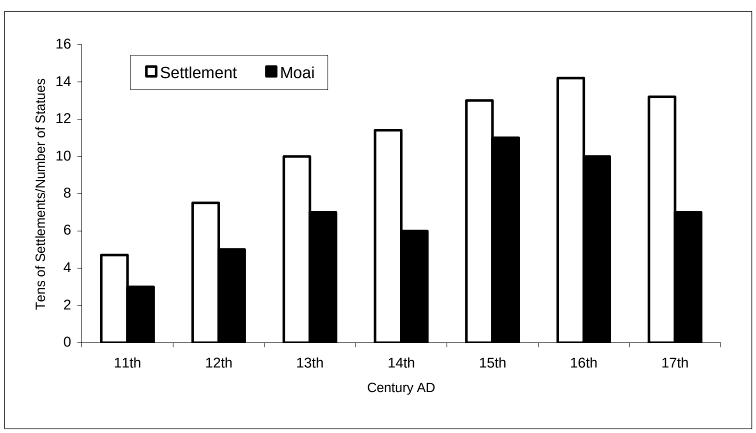


Figure 4.18. Comparison of the frequency of elliptical house occupations (Stevenson 1997) for two southern areas on the island and the number of statues constructed in the southern half of the island (according to OPS analysis) by century.

Although statue construction and transportation in the southern region of the island may have started in the 11th century, energy investment in statuary remains relatively low until the 14th century. In contrast, while energy investment is at a relative minimum for the south in the 13th century, energy on the north coast is simultaneously hitting a peak. Energy investment in statuary in the north then dwindles to a trough in the 14th century only to rebound again temporarily in the 15th century. The obvious differences between trajectories for energy investment in the northern and southern regions are of great interest. While the late investment in the southern region may be partly related to a booming population, the seeming sporadic output in the northern region remains enigmatic.

Discussion

The statue chronology developed for this study appears in many ways to corroborate previous research both on *ahu* and on settlements. This helps to lend support to the OPS analysis, but also to the previous research. Nevertheless, the statue chronology used here must remain provisionary until further fieldwork can directly assess the results. In the meantime, the preceding temporal-spatial examination of energy investment in statuary presents several scenarios or hypotheses that may be justified or rejected through environmental simulations in the next chapter.

Estimates from this chapter's analysis strongly suggest that population size for the island (and possibly for smaller geographic units of the island as well) was proportionate to the number of statues constructed each century. Furthermore, although the two are not necessarily proportionate, there appears to be a correlation between the number of statues constructed and the energy invested in statuary each century ($R^2 = 0.85$ for the entire island; $R^2 = 0.63$ for the northern region; $R^2 = 0.92$ for the southern region). Assuming that population size or density is at least partly dependent on resource availability, there may be an expectation for a correlation (temporal and/or spatial) between the energy invested in statuary and resource availability. Computer simulation of prehistoric resource variability in the following chapter attempts to discern variables or conditions which may underlie and account for both population dynamics and energy investment in megalithic statuary.

CHAPTER 5. SIMULATING PREHISTORIC RAPA NUI

For more than thirty years, anthropologists and archaeologists have used mathematical models and computer simulations in order to understand and explain observed phenomena (Fischer 1994). Unlike physical scientists, "Archaeologists are not able to perform repeated, controlled experiments" (Parker et al. 2002:18). Simulations, however, offer some potential to create an artificial, but realistic, environment in which experiments can be controlled and repeated.

Levin (1999:10) underscores the utility of simulation for anthropologists, suggesting that in current research involving modeling and simulation,

> There is fundamental interest in the evolution of social norms, or of language, and how such group properties emerge from and feed back to influence individual behavior.

Often, the emergence and dynamics of feedback loops create complex adaptive systems that are difficult to understand or simply cannot be explained using traditional economic or mathematical models (Kirman 1993; Ormerod 1999).

Despite the relatively long-standing interest in anthropological simulations, modeling of complex adaptive systems is still not an approach that is widely applied in archaeology. Only in the last fifteen years, with the rise of computing power and the reliance on GIS, have archaeologists begun to publish the results of computer simulations regarding prehistoric populations in an environment that is designed to mimic paleoenvironmental conditions for each population.

Dean et al. (1999) have studied the collapse of the Anasazi in Arizona. Kohler et al. (1999) simulated settlement patterns in the Southwest U.S. Lansing (1999) derived optimal irrigation patterns for Balinese farmers, and Lake (1999) simulated foraging patterns on the Southern Hebridean island of Islay. These projects all have two features in common. The simulations use a two-dimensional environment based on GIS research that allows for considerable spatial variability in resources, and the simulations included agents representing autonomous individuals. As Parker et al. (2003:11) explain, “Agents must act according to some model of cognition that links their autonomous goals to the environment through their behavior.” Thus by including agents in simulations, anthropologists can potentially study not only environmental impact on human populations, but also human impact on the environment and human impact on other humans (both at the individual and group levels). It is the heterogeneity and interactions among agents and resources that equation-based economic models, even for Rapa Nui (see Brander and Taylor 1998), have lacked in the past (Kirman 1993; Ormerod 1998; Parunak et al. 1998).

Simulations do not necessarily provide conclusions for archaeologists but may demonstrate relationships between key variables in order to generate expectations for comparison with empirical data. Simulation may also help to test multiple hypotheses.

A detailed simulation analysis of the environmental prehistory of Rapa Nui would require many variables, hundreds or even thousands of iterations producing millions of analyzable data points, and computing power beyond that of an ordinary desktop computer. Thus, the ensuing analysis is not an attempt at a comprehensive, detailed simulation analysis but rather an introductory effort that can be expanded and refined in future research.

Specifically, this simulation uses the current understanding of broad prehistoric environmental trends to search for or identify plausible trajectories for a few critical island resources. These reasonable conditions may, in turn, help to justify existing interpretations of cultural evolution on the island in terms of population dynamics. And finally, trends in energy investment in statuary calculated in the previous chapter may then be considered in light of both demographic and ecological changes throughout Rapa Nui prehistory.

Identifying Critical Resources

Environments, whether living or prehistoric, are extremely complex, and like all models, any environmental simulation is a simplification of reality. The objective in simulation is not necessarily to represent reality in detail, but rather to approximate reality, or certain processes of interest within reality, with an organized model. In creating a simulation for Rapa Nui, five critical (and interconnected) elements are identified: potable water, timber, rainfall, marine resources, and agriculture. These resources are selected based on extensive literature concerning prehistoric Rapa Nui ecology and subsistence strategies.

Mieth et al. (2002:89) suggest that, "Knowledge about past environmental conditions, particularly about climate and soils is very poor (Louwagie and Langohr 2002)." While the details of environmental conditions are often debated, the variability in explanations presents an ideal application for simulation analysis. Interpretations of the prehistory of critical resources based on extensive research may vary, or even conflict, but present a range of possible values to assign to simulation parameters in iterative testing. That is, the range of possible outcomes in a simulation is quickly and effectively constrained by environmental research, albeit inconclusive or crude in scale in some cases.

The five resources selected as variables for the simulation are not the only natural resources exploited prehistorically. As Martinsson-Wallin (1994) explains, stone quarries may have also played a major role in determining which areas of the island were most favorable and most heavily exploited. Various types of stone quarries may be included in future simulation efforts but are omitted here for several reasons. Most importantly, the fewer variables employed in a simulation, the more meaningful the results may become. Simulations employing many variables are capable of producing a wide array of results, none of which are necessarily significant or testable. Therefore, as a preliminary analysis, this simulation is restricted to just five resources.

Additionally, spatial variability in availability of stone resources may be extremely difficult to model. The fact that hundreds of gigantic statues were carved at the Rano Raraku quarry and transported to all sectors of the island may indicate that long distances did not ultimately prohibit access to stone resources. Furthermore, there is considerable evidence that stone resources were recycled. Obsidian and basalt handheld artifacts may have been transported and retouched over time, statues were sometimes incorporated into the structural architecture of stone altars, and large basalt blocks used in house foundations were often later reused for cooking hearths or cave shelters. While initial stone quarrying may have impacted settlement patterns, constant transporting and recycling of stone resources may have lessened the importance of living in the immediate vicinity of raw materials. Nevertheless, more complex future analyses may include stone resources and other resources not mentioned here.

Potable Water

Spatial variability in access to fresh and brackish water sources is based on a map published by Martinsson-Wallin (1994). Unfortunately, Martinsson-Wallin's work does not refer to the size or dependability of the potable water resources. And after informal survey across the island's interior, it appears that Martinsson-Wallin's map may significantly underrepresent inland springs or upwellings. Rainfall may have also offered a critical and immediate fresh water resource, and one that would be less restricted geographically. *Taheta* (carved stone catchments for rainfall) have been found in various locations on the island. Some of these artifacts may have even been portable. Therefore, fresh water resources may have been similar to basalt and obsidian stone resources in the sense that availability was not static or constantly limited spatially. Without a comprehensive database of *taheta* locations on the island, potable water resources are assumed to be restricted spatially (to those areas mapped by Martinsson-Wallin), but not temporally. In other words:

(1) There existed a certain number of permanent local fresh and brackish water sources on the island that were necessarily exploited regularly by islanders.

Timber

Timber or woody species likely played a major role in Rapa Nui prehistory as a fuel source, for construction of sea-worthy vessels, and for the transportation or erecting of statues (Hunter-Anderson 1998). Although the earliest European visitors to the island seemed to bare witness to an island devoid of woody species, Skottsberg (1956) speculated on, and subsequent research conducted by the Norwegian Archaeological Expedition confirmed, the prehistoric existence of a forest (Heyerdahl and Ferdon 1961). Even so, there was some early consensus (Van Balgooy 1971; Skottsberg 1956; Stevenson 1984) that species diversity on the island had been restricted prehistorically by the relative isolation of the island. However, as more detailed palynological research has been executed, Flenley et al. (1991:114) have remarked, “The pollen record shows that the flora was formerly quite diverse in woody species…” Orliac’s (2000) research appears to agree with Flenley et al. to this extent, identifying more than twenty total woody species that may have at one point forested the island. Despite Rapa Nui’s watery isolation, Orliac (2000) and others (Flenley 1996; Skottsberg 1956) conclude that the majority of the flora reached the island long before human colonization, from origins in Southeast Asia.

The specific uses for different species of vegetation in Rapa Nui prehistory are largely unknown, although speculation on the uses of the famous *Paschalococos disperta* palm has been extensive (e.g. Arnold et al. 1990; Orliac 1989). In a recent study on the eastern Poike Peninsula of the island, Mieth et al. (2003) estimate that palms may have grown at an average distance from one another of 3.5 m. Nearly fourteen million trees (almost 82,000/km^2) may have at one point covered the island, extrapolating from Mieth et al.'s estimate for an island-wide forest. This value is based on the palm species and the assumption that the palms once covered the entire island. There are also the possibilities that palms did not cover the entire island at the estimated density and that other species may have also been dispersed at alternative densities. Stevenson (2002) proposes that palms may have populated higher elevations more densely as a result of higher rainfall, but lower temperatures and exposure to winds may have counteracted benefits from increased rainfall. Furthermore, the relative importance of *Paschalococos disperta* has not yet been convincingly established for Rapa Nui prehistory.

Research on the flora of Rapa Nui has been concerned not only with its prehistoric existence, but also in some cases its subsequent disappearance. The latest or most conservative estimates suggest that complete deforestation took place around AD 1650, when charcoal from woody species appears to be replaced by grassier species (Orliac 2000). This observation implies a drastic and widespread change in cooking fuels on the island. At the other end of the spectrum, Bahn and Flenley (1992) suggest that forest resources had disappeared almost entirely as early as AD 1200.

The majority of research on the prehistoric deforestation of Rapa Nui fixes the deforestation period sometime between the estimate of Orliac (2000) and that of Bahn and Flenley (1992). Flenley (1993) suggests that rapid deforestation may have begun around AD 800 in the southwestern corner of the island and AD 1000 in other areas. Mieth et al. (2003) suggest that *Jubaea* palms experienced rapid clearance on the Poike Peninsula beginning around AD 1280. And finally, Flenley et al. (1991) and Flenley (1993:43) seem to agree that, at least in the southwestern corner of the island, the "last remnants of forest were destroyed by 500 B.P."

Palynological research and testing has, to some extent, helped to propose initial and terminal conditions for the prehistoric timber resources of Rapa Nui. However, the causes and rate of deforestation remain unclear. The literature is somewhat divided by those that believe deforestation was entirely human-induced and those that believe climatic perturbations may have been responsible for decline in woody vegetation. Some have argued that human-induced deforestation is unlikely, especially considering that certain woody species were likely unsuitable for exploitative purposes like canoe construction (Hunter-Anderson 1998; Orliac 2000). As a substitute, major climatic events, droughts or even the impact of the El Niño/Southern Oscillation phenomenon are suggested to be responsible for floral diminution.

Ultimately, however, the timing of deforestation and human arrival on Rapa Nui seem to implicate humans. Even if humans were not directly responsible for cutting or burning forests, they may have been the indirect source of disaster. Hunt (2006) for Rapa Nui, and Athens et al. (2002) for the Hawaiian Islands, have attributed some degree of floral collapse to the human introduction of the Polynesian rat. Although in other cases, researchers have suggested that complete, or even severe deforestation by the Polynesian rat is unlikely (Diamond 2005). Other indirect effects of human arrival (e.g. plant pathologies in imported domesticates) may also bear partial responsibility. Perhaps most persuasive of all in rejecting natural or non-human causes of deforestation is Flenley's reasoning and appeal to palynological records reaching much deeper in prehistory than the arrival of humans on Rapa Nui. Flenley (1993:44) states that "…it seems odd that the forest should survive for 35,000 years—including the major climatic fluctuations of the last ice age and the postglacial climatic peak—only to succumb to drought once people arrived on the island." In sum, although we cannot be certain, circumstantial evidence points in the direction of human causality.

Whether deforestation was a relatively constant and slow process, a short and devastating one, or something more sporadic has yet to be determined. Despite the difficulties in studying the precise details and timing of deforestation, floral studies do offer important constraints for starting and finishing conditions of timber in the simulation:

(1) Prehistorically, Rapa Nui hosted a forest of a variety of woody species.

(2) Based on detailed studies of the palm trees on the Poike Peninsula, fourteen million may offer a rough estimate for the total number of trees populating the island at the time of human colonization.

(3) Deforestation of the island may have reached a significant level by AD 1200 and was probably complete by AD 1500, or at the very latest, AD 1650.

Rainfall

Several studies have identified rainfall as a critical fresh-water resource in Rapa Nui prehistory. Hunt and Lipo (2001:108) as well as Stevenson et al. (2002:18) insist that prehistoric agriculture on Rapa Nui depended nearly exclusively on rainfall. Data for rainfall on the island is limited, spanning only fifty years and collected systematically for only one small area of the island. Publications have suggested an average annual rainfall of approximately 1200 mm at low, coastal elevations (Genz and Hunt 2003; Mieth et al 2002).

Studies extrapolating from existing rainfall records indicate that rainfall may be orographic on the island, affected in part by the central Terevaka volcano. Stevenson et al. (2002) reason that rainfall patterns may be attributable to the northwest-southeast trade winds. Wozniak (2001), on the other hand, considers the northwest coast of the island to be leeward. In reality, spatial variability in rainfall about the island's landscape may be difficult to discern without extensive additional data collection. Furthermore, as Finney (1985:12) explains, Rapa Nui's location in the Pacific may account for climatic patterns that are difficult to summarize:

> At latitude 28˚ south, Easter Island lies in the transition zone between the southeast trades and the westerlies of higher latitudes. In fact, during the winter months from May through September, the island is frequently subjected to unsettled, often rainy weather with spells of strong westerly winds (British Admiralty 1943, II:67).

There is some general agreement, however, that rainfall may increase with elevation. Skottsberg (1956:491) may have been the first to record this observation for the island. More recent studies predict between one-and-a-half (Wozniak 2001) and two (Honorato et al. 1991) times as much rainfall at elevations above 200 m than at coastal elevations. At the same time, it may be important to note for modeling purposes that increased rainfall at higher elevations does not directly translate to increased exploitable resources. Stevenson et al. (2002) stipulate that wind exposure, evaporation, and lower temperatures at higher elevations may offset the benefits of increased rainfall. Nevertheless, elevation seems to be a key factor in measuring rainfall. And despite potentially complicated wind patterns, Wozniak (2001) concludes that rainfall intensity is approximately concentric around the Terevaka volcano—again roughly in line with estimates offered by elevation.

Because of prevailing wind patterns and general concepts such as orographic rainfall, researchers have been able to make educated guesses with regards to spatial variability within Rapa Nui rainfall. The limited longitudinal data available for Rapa Nui rainfall makes temporal variability in rainfall more difficult to fully understand. Genz and Hunt (2003) indicate the standard deviation for yearly rainfall between 1950 and 2000 to be 91.54 mm. Genz and Hunt also suggest that their statistical analyses agree with MacIntyre (2001) in that there appears to be little or no correlation between Rapa Nui rainfall patterns and the El Niño/Southern Oscillation. On the other hand, the analysis of Genz and Hunt remains preliminary considering the simplicity of the correlation tests and the myriad potentially applicable statistical analyses.

Hunt and Lipo (2001:108) conclude that rainfall on Rapa Nui demonstrates a high degree of variation and furthermore that, "…the evidence suggests that droughts are common, and significant departure of rainfall from the average occurs with some frequency." However, there is no discussion at all of what constitutes "a high degree of variation", what threshold may constitute a "drought", or what constitutes "significant departure" from average rainfall. Hunter-Anderson (1998) and Stevenson et al. (2002) refer to the rainfall and the Rapa Nui environment with equally ambiguous terms such as, "variable", "uncertain", and "unpredictable". Simulation of prehistoric environmental parameters may help to deal with variability in more specific or quantitative terms than speculative summaries. The following may serve as constraints for simulation of Rapa Nui's prehistoric rainfall resources:

(1) Rainfall at low (coastal) elevations shows a 50-year average of approximately 1200 mm and standard deviation of approximately 92 mm.
(2) Rainfall, or at least the net effects of rainfall, may be directly related to elevation changes on the island.
(3) Despite variability in rainfall, no clear periodicity in relative decreases or increases of yearly rainfall has yet been identified.

Marine Resources

Timber and rainfall are, and certainly were, critical resources in the Rapa Nui environment. However, they may be different than some other resources in that they served primarily as fuels or means by which islanders accessed other resources that would have been directly consumable. For sustenance, this analysis considers two types of food resources: marine and agricultural. Again, for the purposes of modeling or simulation, terminal and initial conditions are sought in the archaeological and ethnographic record.

Early ethnographic reports for Rapa Nui indicate that marine resources may not have been intensively exploited late in prehistory (La Perouse 1797; Routledge 1919). Furthermore, archaeological excavations conducted by Ayres (1975) appear to corroborate the ethnographic record. More detailed analyses tend to differentiate among different types of marine resources. Martinsson-Wallin and Crockford (2002) posit that while offshore fishing may have lost favor late in prehistoric times, analysis of faunal remains imply that inshore strategies may have played a major role in late prehistory.

Archaeological investigation and faunal analysis present a very different scenario for early prehistoric times on Rapa Nui. Considering that the first settlers on the island likely arrived from tropical eastern Polynesia and descended from a culture with a lengthy tradition of fishing and exploitation of marine resources, an early focus on marine (especially pelagic) prey should not be surprising. The work of Martinsson-Wallin and Crockford (2002) along with the work of Steadman et al. (1994) serves to demonstrate an emphasis on marine mammals and offshore fishing in early subsistence strategies.

Thus, much like in the case of timber resources, extensive research has determined early and late (or initial and terminal) conditions for marine resources.
A decline in exploitation of deep sea prey and perhaps simultaneous uptake of inshore or coastal exploitation appears to characterize a large portion of Rapa Nui prehistory, yet

details of this trajectory remain elusive. There is a strong possibility that deep sea fishing or hunting of marine mammals may have been a practice that was forcibly abandoned with the decline in timber required for construction of sea-worthy canoes. The exact timing or threshold of deforestation that may have prevented subsequent exploitation of pelagic resources is not clear. However, Steadman et al. (1994:91) use subtle archaeological and faunal clues to deduce that, “The decline in exploitation of marine mammals must have been precipitous.” Furthermore, Steadman et al. (1994:91) notice that, “Bones of delphinids are rare, in many cases nearly absent, from Easter Island faunal assemblages younger than c. 500 B.P. (Ayres 1979, 1985).” Their conclusions suggest the approximate timing at which a threshold was crossed. The changing exploitation of marine resources, especially the temporal decline in high-ranked prey could potentially be further understood with additional research on Rapa Nui. Explicit studies to this end have been successful both in eastern and western Polynesia in documenting changes or abandonment of certain marine resources over time, either by cultural or natural causes (e.g., Allen 1992; Allen et al. 2001; Butler 2001; Fraser 2001; Nagaoka 2001, 2002). For the time being, simulation of marine resources in conjunction with other critical island resources may help to interpolate the relative importance of marine resources throughout the island’s prehistory. The following general observations serve as constraints for computer simulation:

(1) Early prehistoric Rapa Nui offered a variety of marine resources for islanders and means (primarily timber) by which these resources could be accessed and exploited intensively.

(2) By about 500 years before present, pelagic resources were no longer exploited with any regularity, and as a consequence, total marine resources available to islanders had diminished greatly in late prehistoric or early historic times.

Agriculture

Agricultural resources are perhaps the most difficult or complicated to model. However, they were clearly a key component to Rapa Nui subsistence, especially in late prehistoric times. Mieth et al. (2002:89) list a number of important domesticates for prehistoric Rapa Nui:

> The Polynesians probably brought a wide variety of nutritious plants to Rapa Nui as, for example, kumara (sweet potato, *Ipomaea batatas*), taro (taro, *Colocasia esculaenta*), uhi (yam, *Dioscorea alata*), maka (banana, *Musa sapientium*), toa (sugar cane, *Saccharum officinarum*) and ti (*Cordyline fruticosa*) (Flenley 1993, Stevenson et al 2002, Zizka 1991, 1989).

Although Hunt and Lipo (2001) and Stevenson et al. (2002) point out the vital dependence of agriculture on rainfall, precipitation is not the only important determinant of agricultural production. Furthermore, Lee et al. (n.d.) argue that, "…rainfall alone is a poor characterization of agricultural yield." Detailed studies on agricultural productivity for prehistoric Rapa Nui have become increasingly popular in recent years (e.g., Mieth et al. 2002; Mieth et al. 2003; Stevenson et al. 2002; Wozniak 2001). However, even these have not reached a level of detail that has proven to be critical in understanding prehistoric agricultural production for other Polynesian islands.

Extensive systematic chemical testing of soils in the Hawaiian Islands provides an example of the type of research that will be required on Rapa Nui for a better understanding or estimate of agricultural productivity in prehistory. Geochemical surveys of soils in Hawaiʻi have attempted to measure soil productivity through elements including phosphorous, potassium, calcium, magnesium, and sodium (Clark and Tamimi 1984; Crews et al. 1995; Vitousek et al. 2004). Above other elements, however, phosphorous (P) appears to be most effective in determining prehistoric agricultural productivity of soils. Furthermore, Crews et al. (1995:1407) have found the "highest P at the 150,000 year-old-site." Phosphorous levels appear to decrease for both older and younger sites, at least in Hawaiʻi.

Vitousek et al. (2004) also concentrate on analysis of phosphorous and ultimately relate agricultural productivity in soils to the age of the volcanic substrate. Dryland (rain-fed) agriculture in the Kohala area of Hawaiʻi Island appears between the 750 mm and 1800 mm isohyets for the 150 ky old Hawi substrate and between the 750 mm and 1600 mm isohyets for the 400 ky old Pololu substrate. Vitousek et al. (2004:1668) conclude that, "Although the particular thresholds of rainfall and substrate age here are specific to the basaltic bedrock of Hawaiʻi, the underlying processes that shape soil fertility (and so the potential for agricultural intensification) are general ones."

Thus, in estimating spatial variability for prehistoric agricultural productivity on Rapa Nui, rainfall gradients and substrate age may be key factors. Ladefoged (personal communication) agrees that the ages of the various volcanic flows that compose the surface of Rapa Nui may be reasonable indicators of agricultural productivity. As a preliminary estimate, Ladefoged suggests that certain young soils on Rapa Nui may be as much as twenty times more productive than the oldest Poike flow.

Potassium-argon dating on Rapa Nui suggests that the easternmost volcano (Poike) was formed at least 3 mya; the westernmost volcano Rano Kau was formed around 2.5 mya; and the central Terevaka volcano was formed roughly 300 kya and connected the older two volcanoes (Flenley et al. 1991). Based on the work in Hawai‘i by Vitousek and colleagues, we may assume that the ages of the varying volcanic soils result in higher productivity for the younger Terevaka region and moreso for the even younger soils surrounding the post-shield-building cinder cones on the flanks of Terevaka (the central southern area of the island). However, it may be important to note that Ladefoged et al. (2005:103) conclude that, “Even the younger volcanic substrates of the interior of Rapa Nui have been leached of their nutrients and would have been a relatively poor horticultural environment during the prehistoric period.”

In addition to substrate age and rainfall, the slope of the terrain may have acted as another determinant of spatial variability for agricultural potential on Rapa Nui. Wozniak (2001) notes a predilection for gardening in flat or concave landforms on Rapa Nui, inferring that these areas may have acted as traps for both moisture and nutrient retention. Furthermore, gardening on steep slopes most likely had a lower return on investment than for flatter terrain as a result of the energy required in accessing the gardens and transporting materials to and from the cultivated areas.

Changes in both climate and technology may have created temporal variability in agricultural potential equally as important as spatial variability for Rapa Nui. In many ways, dryland agriculture productivity is at the mercy of rainfall patterns. Both short-term and long-term climatic perturbations may have induced periods of increased or decreased rainfall that in turn affected crop success. At this point, understanding of these prehistoric perturbations remains limited. Without additional knowledge, the most appropriate manner to model rainfall may be to approximate variability observed over the last half-century by Genz and Hunt (2003).

There were also technological changes in the agricultural prehistory of Rapa Nui that likely led to major increases in agricultural productivity. These changes came in the form of gardening techniques and available domesticates. Stevenson et al. (2002) and Wozniak (2001) identify several agricultural techniques that likely allowed for increases in agricultural productivity: rock mulching, rock veneer, stacked boulder concentrations, *pu* (planting holes in rocky areas), *manavai* (gardens enclosed by stacked, circular rock walls), and planting circles (gardens enclosed by a ring of small stones). These techniques may have helped to enhance retention of nutrients and moisture and also to protect crops from winds and salt spray. Wozniak's (2001) work on the northwest coast of the island indicates that these technological improvements may have first appeared around AD 1200.

Of all the domesticated plants in prehistoric Rapa Nui, the sweet potato appears to be referred to most commonly as the single most important agricultural product for the island (e.g., Stevenson 1984; Wozniak 2001). The sweet potato is a crop that can tolerate significant variability in rainfall, and it is possible that as Hunter-Anderson (1998:96) proposes, "Sweet potatoes (*Ipomoea batatas*), obtained from [South America], became the most important food crop since they could tolerate a wide range of temperatures."

McCall (1979) ventures to guess that dryland taro may have been an important crop for the northern areas of the island but again suggests the sweet potato as the staple for the southern region. While the sweet potato does not require the same depth of cultivation as yams or taro, it does require friability of soil (Yen 1974). The timing for the introduction of the sweet potato as a cultigen is not yet clear. Stevenson et al. (2002) propose that the sweet potato arrived around AD 1400. While acknowledging that the earliest radiocarbon date associated with sweet potato in Rapa Nui is AD 1437-1619 (cal. 1 sigma), Wallin et al. (2006) interpret indirect archaeological evidence to suggest an introduction of sweet potato in the 13th century. Green (2006) and Martinsson-Wallin (2002) both suggest an earliest date for the sweet potato's arrival around 1100, referring again to indirect archaeological evidence. In sum, the following conditions may help to constrain computer simulation of prehistoric agricultural resources:

(1) Although productivity may be related directly to chemical balances within soils, the age of volcanic substrates may be a reasonable proxy measure for agricultural potential on Rapa Nui. However, the overall agricultural productivity on the island may have been relatively poor.

(2) Rainfall was a key component in dryland agriculture. Variability in rainfall (both spatially and temporally) likely led to variability in agricultural productivity.

(3) Developments in gardening technology around AD 1200 may have added to or even multiplied agricultural potential.

(4) The introduction of sweet potato sometime around AD 1400 may have added to or even multiplied agricultural potential.

Interaction of Resources

One of the advantages of computer simulation and a complex systems analysis of prehistoric Rapa Nui resources is that non-linear relationships may be identified and modeled with some accuracy. Although only five critical resources are identified here, these resources may have interacted to form complicated temporal and spatial patterns of resource abundance and variability. Simulation parameters are discussed in detail below.

Timber is directly influenced by the three other resources. Presumably, forests and vegetation for pre-contact Rapa Nui were dependent on rainfall. Therefore, the initial distribution of timber resources may be based on rainfall isohyets for the island. Simulation controls allow for the user to determine the precise relationship between rainfall intensity and timber distribution. Timber, specifically the rate of deforestation for any given region on the island, is also dependent on both marine resources and agriculture. It is possible that those areas most intensively inhabited and exploited for food resources would be the most rapidly deforested (at least by direct human causes). At least for agricultural intensification, forests must be cleared to make room and allow direct sunlight for crops. In order to access nearby marine resources, islanders may have likely selected the nearest, most convenient timber for construction of seaworthy canoes. Thus, those regions with the greatest marine and agricultural resources might also experience the greatest rate of deforestation. Regions with fewer marine or agricultural resources may still experience deforestation but at a lesser rate.

Rainfall, conversely, is the only one of the four resources modeled to be completely independent of the others. Although in some simulations (especially for industrialized regions or societies) humans may have an indirect impact on microclimate or precipitation patterns, such effects are not included in the simulation for Rapa Nui.

Marine resources are impacted directly by timber in this model. The relationship is one based on a threshold value for deforestation. The model suggests that with ample supply of timber for construction of sea-worthy vessels, marine resources were fully exploitable. However, as timber resources reached a critically low value, deep-sea resources may have become inaccessible to islanders. Therefore, once deforestation surpassed a threshold value, marine resources were still available but to a lesser extent.

Agricultural resources are partially determined by rainfall. Even the most fertile or productive of soils are only exploitable with sufficient rainfall. Thus, yearly rainfall values determine the short-term productivity for different soils or volcanic substrates on the island. However, isohyets for the island also have a long-term or more permanent impact on agricultural productivity for soils. In general, rainfall may increase with elevation, in turn benefiting agricultural productivity up to a certain point. However, at particularly high elevations, wind exposure, evaporation, and lower temperatures may all reduce the impact or benefits of increased rainfall. Furthermore, in some areas, high levels of rainfall may lead to, "leaching of base cations and P [causing] reductions in these essential rock-derived plant nutrients…(Kirch et al. 2004, Vitousek et al. 2004)"(Lee et al. n.d.).

There is also the possibility that agricultural intensification created a feedback loop that consequently affected agricultural potential in future generations. Research on Hawaiʻi Island suggests that intensive agriculture for a prolonged period of time led to a human-induced reduction in available P (Vitousek et al. 2004). Organic or rock mulching may potentially slow or counteract soil degradation, but does not appear to have played a major role in dryland agriculture in prehistoric Hawaiʻi. Recent research on Rapa Nui suggests that prolonged human exploitation and cultivation of soils may have indeed depleted soil nutrients in some regions (Ladefoged et al. 2005). Furthermore, geochemical analyses also suggest, in a preliminary manner, that vegetative and lithic mulching may have been used on Rapa Nui to enhance or retain soil fertility. The simulation described here does not include degradation or depletion of agricultural potential resulting from prolonged intensive exploitation. However, this phenomenon is one that may be included in the model in future analyses.

The effects or relationships between separate resources are not particularly complicated as initially parameterized. However, once hundreds of years or iterations pass in a simulation, one resource may experience not only a direct relationship with another resource but also secondary or even more complex relationships. These relationships and their unique effects within the simulation can be extremely difficult to discern (Ormerod 1998), and a thorough analysis of such effects is beyond the scope of the work here. The ensuing text and following chapter, nevertheless, discuss a few of the potential variable values tested in the simulation and the apparent effects or patterns created by these variable values in Rapa Nui prehistory.

Population

Although the prehistoric environment of Rapa Nui is worth studying in its own right, the context here is anthropological. Therefore, the primary concern is how humans interacted with their surrounding environment. Clearly, the extent and intensity with which humans interacted with environmental resources depended on the size and distribution of the prehistoric population around the island. Data, knowledge, and speculation all help to determine demographic constraints for an agent-based simulation. Specifically, constraints are developed for conditions at the time of colonization, for a population at its peak, and for the period of growth in between these two times.

In calculating population growth rates elsewhere in Polynesia, Terrell (1986) systematically employs a founding colony of forty individuals. This figure may not be accurate for all Polynesian islands, but sets a precedent for modeling and simulation in the region. The timing of the arrival of Rapa Nui's first Polynesian colony is often debated. A single radiocarbon date from the Poike ditch on the eastern end of the island provides an often-disputed earliest date of ca. AD 400 (Heyerdahl and Ferdon 1961:395). However, considering the larger suite of radiocarbon dates now available for the island, Martinsson-Wallin and Crockford (2002:254) conclude that, "Evidence for occupation of Rapa Nui prior to AD 800 is scant." After AD 800, on the other hand, dated samples for both residential and ceremonial sites become increasingly plentiful. Hunt and Lipo (2006) have suggested a recent colonization date of AD 1250, proposing that earlier dates need revision. However, given the quantity of dates that currently place colonization well before AD 1250, Hunt and Lipo's hypothesis is difficult to accept without a more thorough and explicit statistical review. For simulation purposes at this point, anywhere between AD 800 and 1000 may serve as a conservative colonization date.

Hunt and Lipo (2001) suggest that, centuries after colonization, a population of approximately 10,000 would have reached, or at least closely approached, the carrying capacity of the island. Other researchers have also implied that, at its peak, the Rapa Nui population surpassed the carrying capacity of the island (Bahn and Flenley 1992; Diamond 1995, 2005; Flenley and Bahn 2003; Kirch 1984).

Bahn and Flenley (1992) and Flenley and Bahn (2003) suggest that the prehistoric population reached its peak around AD 1600; Stevenson (1984, 1997) interprets data from obsidian hydration analyses of residential structures at various locations in the southern region of the island to indicate that the population peaked sometime during the 16th century; and Love (personal communication) interprets evidence from dated ceremonial structures to indicate that the population peaked shortly before the beginning of the 16th century. Assuming a maximum population of ten thousand, these estimates translate to a long-term exponential population growth rate of between 0.69% and 0.79% per year, which is slightly less than the lowest documented rate (0.9%) in Polynesian history (Terrell 1986). However, these growth rates are still plausible, considering the context of a subtropical island with limited biodiversity and natural resources.

To summarize, the following may help to constrain the agent-based simulation:

(1) Rapa Nui was likely colonized between AD 800 and 1000.

(2) The island population reached a peak sometime between 1500 and 1600.

(3) Although the growth rate of the prehistoric island population could have assumed any value, documented rates for Polynesia suggest a realistic range between 0.9% and 4.0% per year (Terrell 1986).

Designing a Simulation for Rapa Nui Prehistory

Computer simulation and agent-based modeling provide the distinct advantage over other more traditional approaches to archaeological inquiry of being able to simultaneously analyze variation over space *and* time. Simulations described here are performed using NetLogo 3.0.2 (Wilensky 1999). NetLogo is a cross-platform multi-agent programmable modeling environment. NetLogo was chosen as the modeling environment because it is free to download and use, the language is relatively easy to learn, and the software has been updated regularly over the past six years—suggesting that this will be a program with a relatively long lifespan.

Spatial parameters for the Rapa Nui environment were first developed using ESRI software, ArcView 3.2 and ArcGIS 8.2. All shapefiles generated with ESRI software were files were later exported for use in NetLogo. For simulation purposes, the Rapa Nui landscape was divided into 300m x 300m cells or zones (patches). There are a total of 1,841 land cells in the simulation, covering roughly 166 km^2. The spatial scale allows for considerable detail or variation within the Rapa Nui landscape and at the same time constrains the simulation to a size manageable for desktop computers.

The simulation is designed so that each iteration represents one year's time. Clearly the environment and resources within the environment fluctuate at smaller scales.

Future versions of the simulation can easily incorporate seasonality into the simulation by allowing resource values to update and agents to act several times within a single simulation-year. The consequence of adding seasonality to the simulation, however, is that the potential outcomes of the simulation increase exponentially, making comprehensive exploration and systematic study of the simulation-space much more difficult. The one-year-per-iteration scale also helps to constrain the simulation analysis for efficient desktop processing.

The focus of the simulation is on the years between AD 1000 and 1700, in order to generate data that can later be compared to estimates for energy investment in statuary from the previous chapter. However, all executions of the simulation begin at a colonization date of AD 700. This helps to ensure that the time period of particular interest will not be influenced by anomalous events associated with the startup of the simulation.

Virtual Potable Water

Potable water resources are perhaps the most simplistic in the simulation. While the locations of these resources are fixed in space, the user may determine the distance at which islanders are willing to live from (and travel to) potable water sources (see Figure 5.1). Areas of land beyond the cost-distance (in level-kilometers) defined by the user-defined threshold value are uninhabitable to islanders in the simulation. The water resources, while limited spatially, are not limited in quantity.

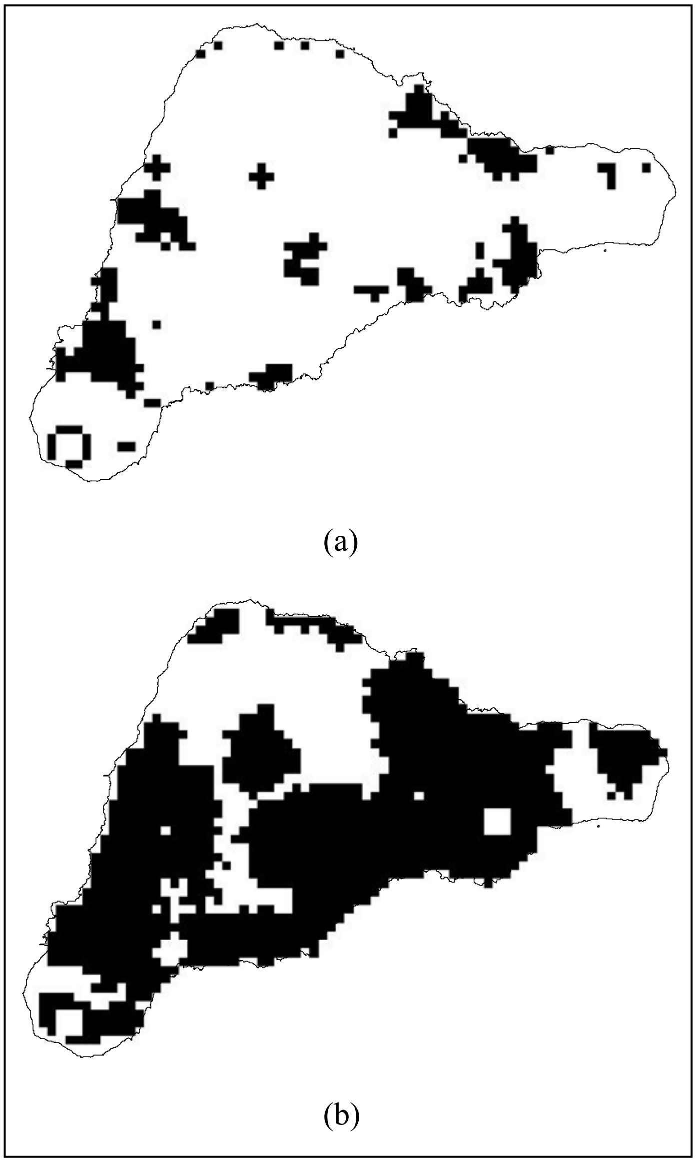


Figure 5.1. Dark areas indicate cells inhabitable by agents based on access to potable water sources. Figure (a) displays the distribution of inhabitable cells when spatial restrictions for potable water sources are severe. Figure (b) relaxes spatial restrictions for water sources.

Foresting and Deforesting a Virtual Rapa Nui Landscape

For the simulation, trees are originally distributed randomly across the landscape (Figure 5.2). The user may alter the range from which the random number of trees is drawn by adjusting the user-variable *trees* (see Appendix B for an explanation of variables and user interface). For example, setting *trees* to a value of

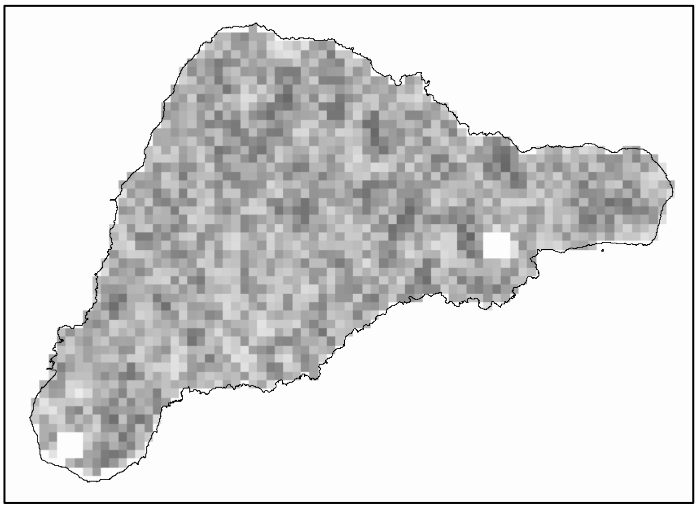


Figure 5.2. Simulation view of initial randomly-distributed timber resources on Rapa Nui. Darker cells indicate greater resources. Timber in this view is not dependent on rainfall.

8,000 creates a forested landscape in which each cell (300m x 300m) contains a random number of trees between 0 and 8,000. Although this may not be the most accurate representation of conditions of forests on Rapa Nui at the time of colonization, a random process is used for lack of more detailed information on prehistoric forests. The user may also select whether the number of trees in each cell is influenced by the amount of rainfall for that cell (or elevation) by toggling the *rain-dependent* variable to ON or OFF. When the switch is set to ON, each cell's tree value is multiplied by the isohyet value from the variable labeled *iso-a*, *iso-b*, or *iso-c* depending on the cell's elevation (see Figure 5.3). The isohyet variables are explained in more detail below.

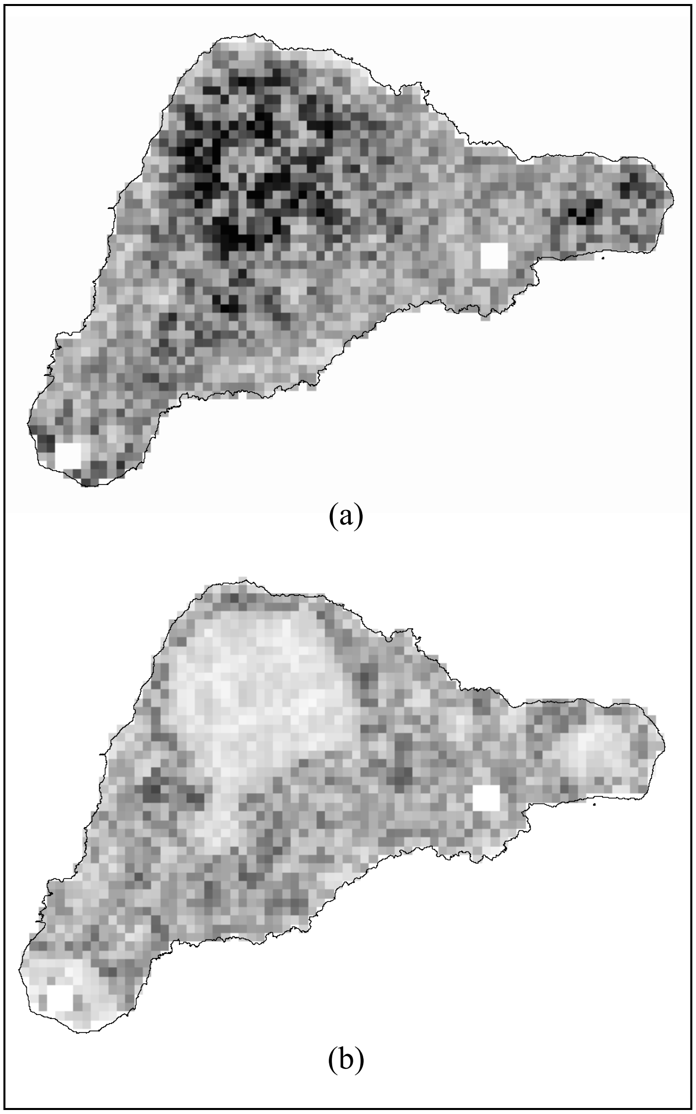


Figure 5.3. Simulation view of initial timber resources on Rapa Nui when timber resources are dependent on rainfall. For figure (a), the benefits of increased rainfall increase with elevation on the island. For figure (b), the benefits of increased rainfall increase up to 200m elevation and then decrease at higher elevations.

While the initial conditions for Rapa Nui forests may be subject to debate and further research, they are not particularly important in developing the current model. Assuming the effects of deforestation only impacted islanders once a threshold value was reached, the rate of deforestation becomes far more important that the initial conditions of timber distribution. The method by which the island was deforested is not clear, although Mieth et al. (2003) indicate that fire may have been used. Fire can be particularly destructive for forests, and the effects may be related to the relative density of the forest (Wilensky 1998). Thus, while fire may have been an effective mass-deforestation tool early on, its efficiency likely decreased as forests became sparser. Similarly, manual felling of trees may have become more difficult over time as forests receded and greater distances separated islanders from their timber sources.

The possible decreasing efficiency in human-induced deforestation over time may have, to some extent, offset the impacts of an increasing demand for timber from a growing island population. The current model accounts for these factors by implementing an exponential function to calculate forest decline over time. An exponential function is only one of many that could be used to effectively model prehistoric deforestation. The number of trees (*T*) in any given cell at time ***t*** is:

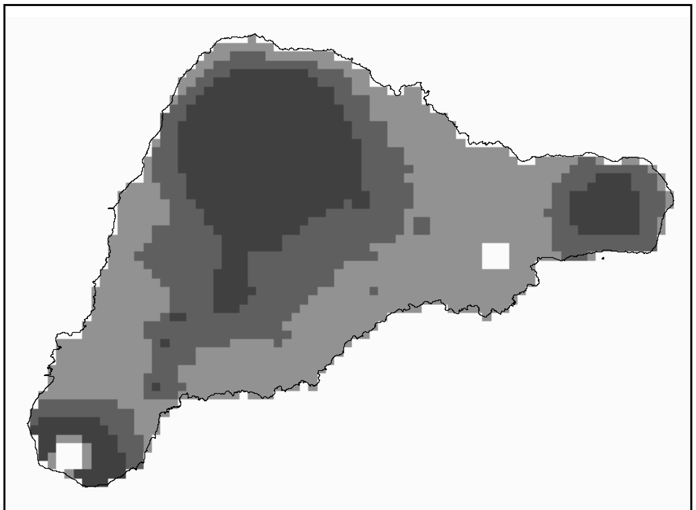
$$T_t = T_{t-1}e^{kr} \qquad \text{(Equation 5.1)}$$

The constant *k* is a measure of each cell's productivity (total yield of agricultural and marine resources) relative to the cell with maximum productivity on the island at time *t*. The constant *k* suggests that cells ideal for habitation will be deforested more rapidly than other cells (to make room for settlements, agriculture, etc.). In Equation 5.1, *r* represents the rate of deforestation applied to all cells. Values for *k* and *r* were selected for this simulation so that deforestation reached threshold values around the time period suggested by archaeological and palynological research. Precise values for constants in Equation 5.1 are somewhat arbitrary, and in order to maintain a closeness-of-fit to constraints for initial and terminal conditions in the model, values for *k* and *r* must be selected based on T_0 (initial timber values).

Virtual Rainfall

Rainfall parameters in the current model allow for considerable flexibility. Rainfall can be random from year to year (or iteration to iteration). The user may select the average rainfall value (in millimeters) using the *rain-1* variable. The *rain-1-range* variable determines the range of variation about the mean value. Setting *rain-1* to 1200 millimeters and the *rain-1-range* variable to 200 millimeters suggests that each year rainfall at low coastal elevations will be a random value between 1000 and 1400 millimeters. These conditions approximate rainfall data collected for the island during the last fifty years described by Genz and Hunt (2003).

As opposed to random rainfall, the user may also choose cyclical rainfall. Cyclical rainfall may account for up to two separate cycles in rainfall variability. The *cycle-1* variable determines the number of consecutive years or iterations in the simulation for which rainfall conditions determined by the *rain-1* and *rain-1-range* variables are applied. The *cycle-2* variable determines the number of consecutive years


(a)

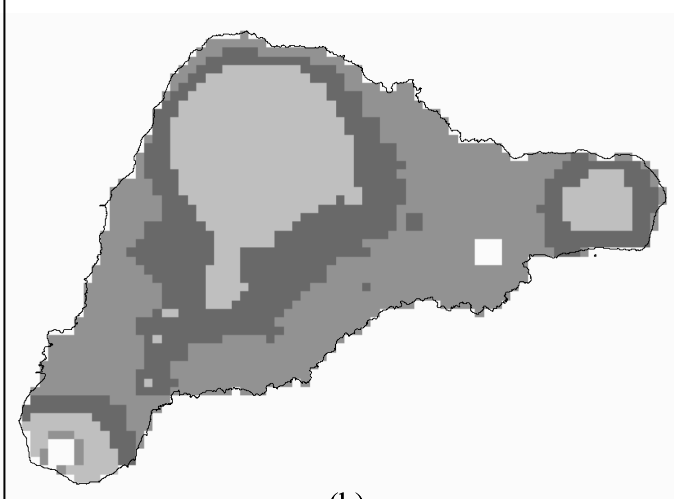

(b)

Figure 5.4. Simulation view of rainfall on Rapa Nui. Darker areas indicate increased rainfall. Figure (a) indicates higher levels of rainfall at higher elevations. Figure (b) indicates increased rainfall up to 200m elevation on the island and a decrease in the benefits of rainfall at the highest elevations on the island.

following the first cycle for which rainfall conditions are determined by the *rain-2* and *rain-2-range* variables. Thus, in future models for the Rapa Nui environment, the island may experience alternating cycles (with differing durations) rainfall and variability.

The isohyet variables offer multipliers for rainfall values at different elevations on the island (see Figure 5.4). Rainfall values for all cells at an elevation of less than 100 m are multiplied by the value selected for *iso-a*. Rainfall values are multiplied by the value selected for the *iso-b* variable for all cells between 100 m and 200 m elevation. And for cells above 200 m elevation, rainfall values are multiplied by the value selected for the *iso-c* variable. Realistic values for the isohyet variables are difficult to determine without extensive testing of their effects on the simulation. While several studies have referred to increased rainfall at higher elevations, the benefits of increased rainfall (at least in terms of agricultural production) may not be proportional to the rainfall itself at the highest elevations on the island.

Virtual Marine Resources

Availability of marine resources in the computer simulation is determined by each cell's proximity to coastline permitting access to the ocean (Figure 5.5). Presumably, coastline characterized by steep and treacherous cliffs (as is the case for much of Rapa Nui's coast) did not allow for onshore fishing or launching of fishing vessels.

Each cell in the simulation is assigned an average slope value based on interpolations from a contour map. Land cells that have at least one adjacent ocean cell comprise the shoreline. The user may choose between values of 5, 10, and 15 degrees

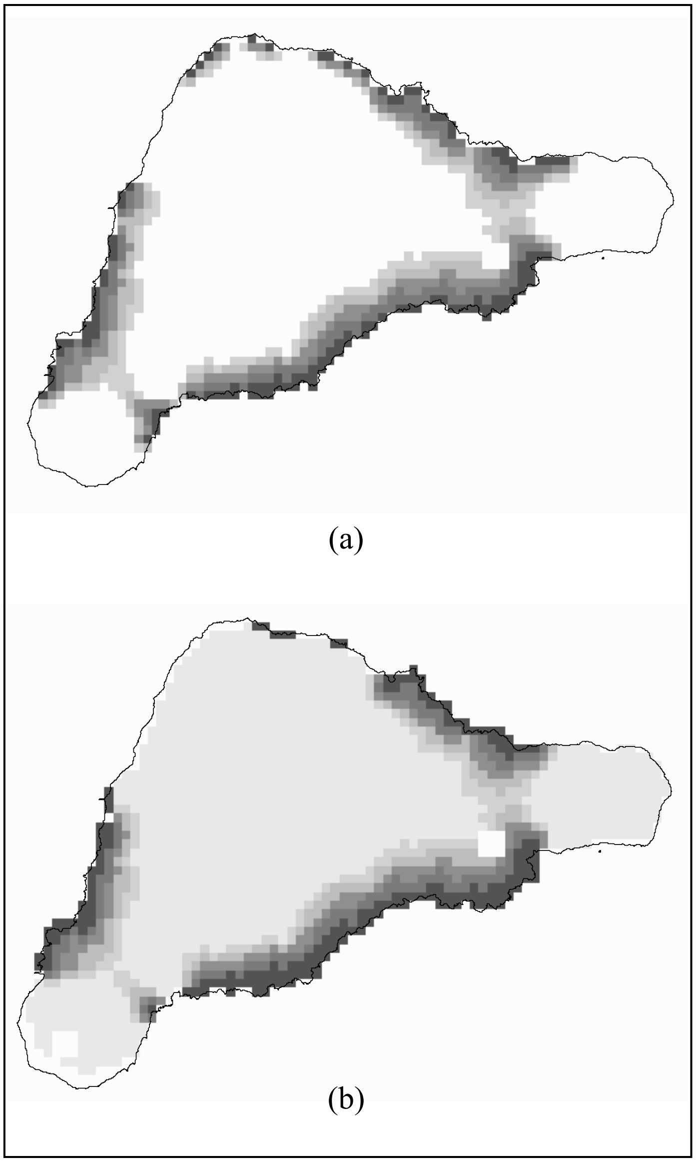


Figure 5.5. Simulation view of marine resources on Rapa Nui. Darker areas indicate those areas with more immediate access to shoreline and increased marine resources. Figure (a) considers all coastal zones with a slope of less than ten degrees to permit access to marine resources, and all zones up to 5km (flat terrain or equivalent shorter distance with steeper terrain) from coastal access shoreline to enjoy marine resources. Figure (b) considers all coastal zones with a slope of less than five degrees to permit access to marine resources, and all zones up to 11km (the entire island) from coastal access shoreline to enjoy marine resources. In both cases, marine resources decrease with distance from the shoreline.

(from the *coastal-access* variable) as the steepness or slope of the shoreline that prohibits coastal access. Choosing a value of 5 degrees severely restricts coastal access, while a value of 15 degrees allows islanders to access marine resources despite steep shoreline terrain.

Proximity to coastal access for each cell is a measure of the ease in access from any habitable land cell to the nearest shoreline cell permitting access to the ocean. The "ease in access", in turn, is calculated as the distance traversed (or number of cells traversed) multiplied by the slope of the terrain (or each cell) traversed. The user may manipulate the variables labeled *range-a*, *range-b*, *range-c*, …, *range-k* to determine the amount of marine resources available (or effectively the number of people that may be supported by marine resources) at various cost-distances from coastal-access shoreline. Variable *range-a* determines the amount of marine resources (or number of islanders sustainable) for cells residing less than one kilometer (on flat terrain—or shorter distance on steep terrain requiring a roughly equivalent amount of energy to traverse) from coastal-access shoreline. Variable *range-b* determines the amount of marine resources (or number of islanders sustainable) for cells residing between one and two level-kilometers from coastal-access shoreline. Variable *range-c* determines the amount of marine resources available on cells residing between two and three level-kilometers, etc.

Presumably, the value for *range-a* should be greater than the value for *range-b* which should be greater than the value for *range-c*, and so forth (i.e., areas closer to coastal-access shoreline benefit more from more immediate access to marine resources). By setting a *range* variable to zero, the user may determine a distance from coastal-access shoreline at which marine resources were no longer beneficial. For example, by setting *range-c*, *range-d*, *range-e* and all subsequent *range* values to zero, the user suggests that at any distance greater than three level-kilometers from the shoreline, marine resources were of no benefit to islanders.

Each year, or iteration, cells maintain the same value for marine resources from the previous year, unless deforestation has reached a threshold value. For the current model, the deforestation threshold for each cell set to an arbitrary value. That is, once the timber value of a cell drops below the arbitrary value, marine resources become proportionate to the amount of timber remaining in the cell. However, even as deforestation may have eliminated access to pelagic resources, islanders may have still exploited onshore resources. Thus those cells that offer marine resources initially will always provide some marine resources. In other words, even if pelagic resources are no longer available, a small population may be sustained by onshore marine resources in cells near coastal-access shoreline.

Virtual Agriculture

Initial spatial variability in agricultural resources is determined by two factors in this model. First, the cells that compose the virtual landscape each pertain to a specific volcanic substrate. The ages of these seven distinct substrates are assumed to play a major role in determining their agricultural productivity (see Figure 5.6). The user may manipulate the relative productivity for each volcanic substrate by adjusting the volcanic substrate variable values (*HH*, *PO*, *RA*, *RK*, *TA*, *TE*, and *TR*). These variable values

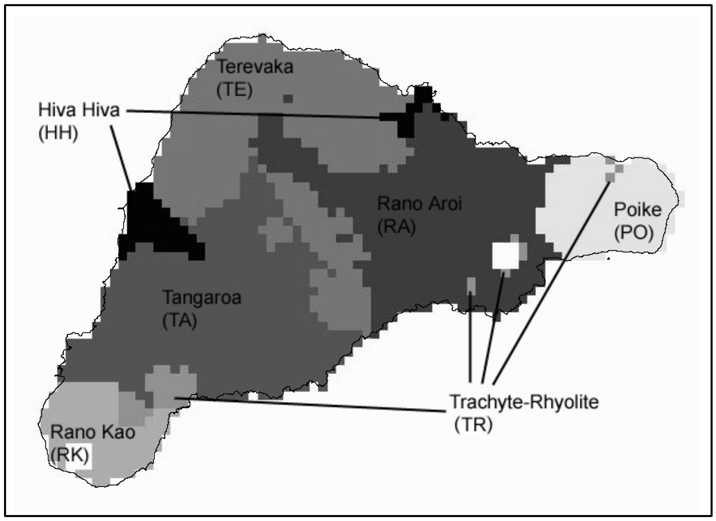


Figure 5.6. Simulation view of volcanic substrates (after González-Ferrán et al. 2004).

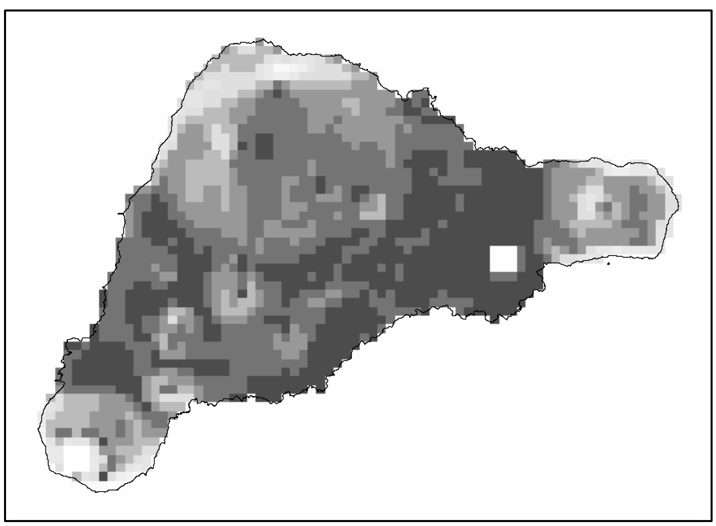


Figure 5.7. Simulation view of the slope of terrain. Darker areas indicate flatter terrain. Agricultural resources are inversely related to the slope of the terrain.

represent the maximum number of islanders that can be sustained by agricultural production in each 300 meter by 300 meter zone.

The second factor to determine initial spatial variability in agricultural resources is the slope of the terrain (see Figure 5.7). The maximum potential agricultural productivity for each zone is multiplied by an inverse slope factor. This factor is applied to account for diminished returns on agricultural production in steep zones as a consequence of the extra energy required to develop and harvest these areas, and greater runoff of rainfall. Perfectly flat terrain maintains the maximum potential agricultural productivity value, but the maximum agricultural productivity of zones characterized by extremely steep terrain is greatly reduced (see Figure 5.8). Polynesian cultures, like many cultures from around the world, were certainly able to use the slope of the terrain to their advantage in agricultural production. However, this was often through cultivation at the base of slopes or on constructed terraces. In dividing up the simulation environment into 300-meter by 300-meter cells, each cell in the simulation is assigned an average slope value. Thus, even where islanders were cultivating at the base of slopes, the *average* slope value for the region is likely to be relatively low, given the mix of slope and area at the base of slopes where terrain levels out.

Subsequent temporal variability in agricultural resources is determined by three factors: rainfall, gardening technology, and the introduction of the sweet potato as a staple crop. The maximum agricultural potential determined by the volcanic substrate underlying each zone is based on a year with average rainfall (1200 mm). Therefore, the yearly agricultural potential value is multiplied by the ratio of rainfall to average rainfall,

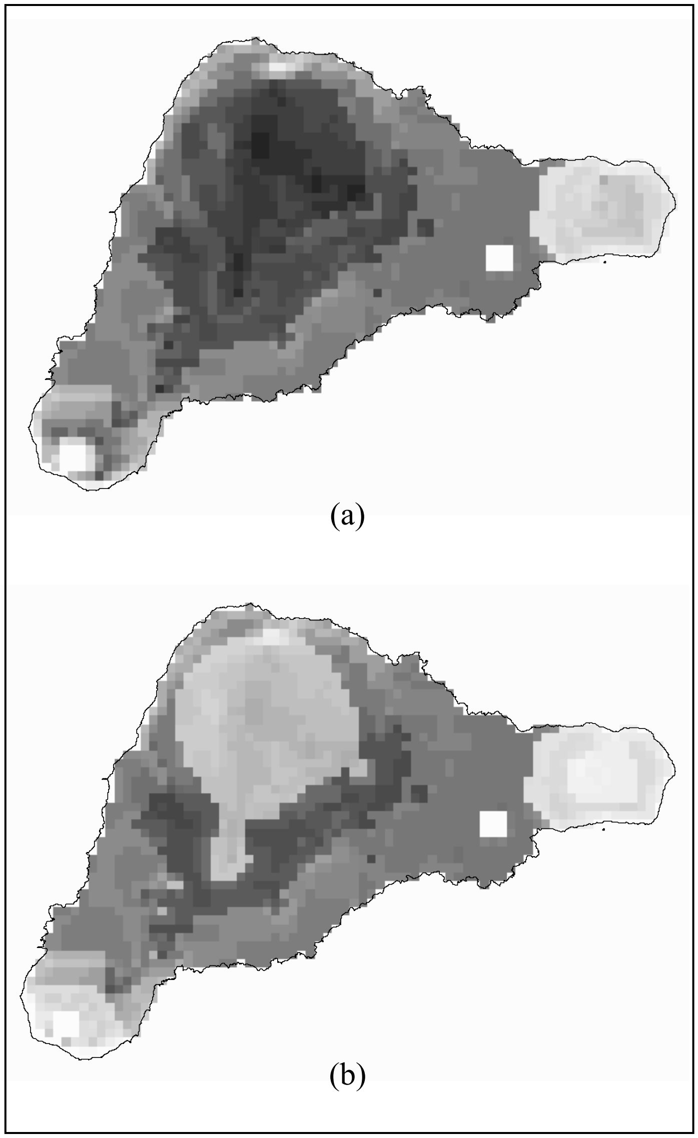


Figure 5.8. Simulation view of agricultural resources (based on soils, rainfall, and slope). Darker areas indicate increased agricultural resources. Figure (a) is based on rainfall resources that increases with elevation. Figure (b) is based on rainfall resources that increase up to 200m elevation and decrease at the highest elevations on the island. The relative lack of archaeological or agricultural remains at the highest elevations on the island may indicate that there was indeed an elevation cutoff at which increased rainfall no longer offered increased benefits.

so that particularly wet years lead to better agricultural yield and exceptionally dry years produce a relatively small agricultural yield.

The user may determine the precise date and benefits of advances in gardening technology by manipulating the variables *gardening-techniques* and *gardening*. The value for the *gardening-techniques* variable determines the year in the simulation in which islanders begin to experience increased benefits. The value for the *gardening* variable is the factor by which each volcanic substrate's agricultural potential is multiplied. The sweet-*potato-introduction* and *sweet-potato* variables have effects corresponding to the *gardening-techniques* and *gardening* variables in order to account for increased agricultural productivity with the arrival of the sweet potato to Rapa Nui.

Adding Virtual Islanders to the Virtual Island Environment

In order to determine the effects of resource variability over time and space, virtual islanders are included in the simulation. The user determines whether the original colony is distributed randomly about the landscape or if all individuals begin in a zone at Anakena beach (in accordance with oral tradition) by toggling the *Anakena* variable. The original colony is divided between 50% males and 50% females. Females are each assigned a maximum number of children that they may bear over the course of a lifetime.

The agents and their directives in this simulation are purposefully designed to be simplistic. This helps to ensure that their actions and the patterns observed in the model are primarily induced by environmental variability rather than behavioral variability implemented by the simulation designer.

Agents' only tasks are to search for resources, consume resources, produce offspring (only female agents), and die. Thus, each agent begins each year or iteration by determining if there are sufficient resources in his or her cell, given the number of agents in the same cell. If resources are sufficient, the agent does not move. If resources are not sufficient, then the agent moves to the cell within a five kilometer radius with the greatest ratio of resources to agents. Each agent consumes exactly one resource (agricultural or marine) each turn. If an agent cannot acquire resources after moving to the most favorable cell, the agent dies (is removed from the simulation) and the age-at-death value is recorded. In addition to the deaths of agents that cannot find sufficient food resources, every agent has a fixed probability of dying, given their age range. These probabilities are calculated so that agent deaths in the simulation closely reflect age-at-death statistics determined by studies conducted by Alfonso and Trejo (n.d.), Shaw (2000), and Seelenfreund (2000) for 620 individual skeletons from Rapa Nui (see Table 5.1).

There are many factors that could have contributed to agent deaths and variability in death rates over time (disease, warfare, etc.). However, thorough data on the most common causes of death are not available. This may be an avenue of further investigation for a simulation analysis of Rapa Nui prehistory.

Female agents that have not already given birth to their maximum number of bearable children may produce one new agent as offspring. The probability of a female agent (of reproductive age) actually bearing offspring each year is determined by a "fecundity" constant. Over the course of the simulation, agents simply repeat their tasks of searching for resources, reproducing, and dying.

Table 5.1. Age-at-death statistics for different age ranges in skeletal studies on Rapa Nui by Alfonso and Trejo (n.d.), Seelenfreund (2000), and Shaw (2000) for 620 individuals. These statistics were used to calculate each agent's probability of dying (regardless of availability of resources) at specific ages. Probability of death for agents over 40 was determined so that very few (less than 5%) of the population survives to ages of 60 years or greater.

Age (years)	% of Collection	Probability of Death (Simulation)
0-2	10.6	0.0367
3-12	27.4	0.036
13-18	10.3	0.03
19-24	5.2	0.0174
25-29	8.9	0.0415
30-40	15.6	0.0477
40+	21.9	0.15

Summary

This chapter offers a brief literature review for each of five critical environmental resources (timber, rainfall, marine, agriculture) and their cumulative effects in critical resource distribution (Figure 5.9), in order to determine constraining values in a computer simulation. Research for population dynamics is discussed, and finally the chapter presents details on the specific implementation of population and ecological variables in an agent-based NetLogo simulation. The user interface of the simulation is presented in Appendix B.

The variables and simulation are specifically designed to help monitor and investigate the interaction between humans and the prehistoric island environment. While the simulation may not provide evidence or conclusions directly applicable to Rapa Nui prehistory, the process may help to demonstrate where observations and

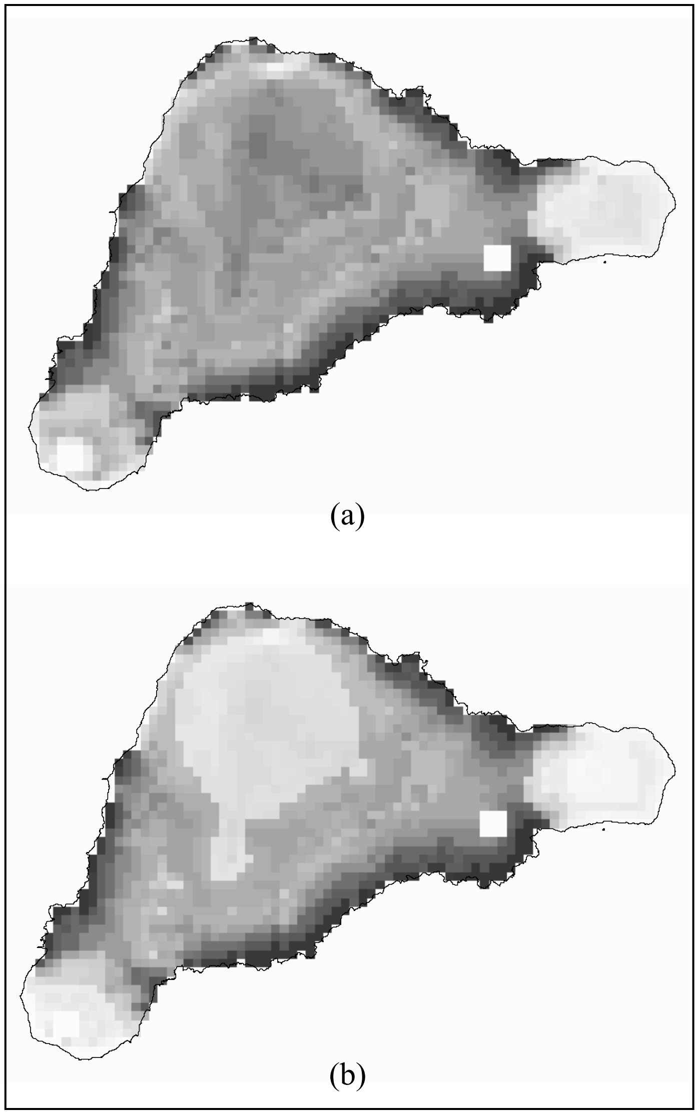


Figure 5.9. Simulation view of initial marine and agricultural resources combined. Darker areas indicate increased total food resources available in each cell. Under initial conditions marine resources may outweigh agricultural resources. However, these conditions change throughout the simulation with deforestation and the introduction of gardening technologies and the sweet potato. Figure (a) is based on rainfall resources that increase with elevation. Figure (b) is based on rainfall resources that increase up to 200m elevation and decrease at the highest elevations on the island.

speculation on the island may be well-founded, where speculation or interpretations have gone too far, and what aspects of the island culture and island ecology require further investigation.

Temporal and spatial variability in resources directly influences the size and distribution of the prehistoric island population in the simulation. Carefully tracking patterns in the simulation and subsequently comparing those patterns to trends in energy investment in monumental statuary (developed in the previous chapter) offers the potential to investigate the interplay between prehistoric resource availability, population dynamics, and one form of cultural elaboration (statuary). These comparisons are made in the following chapter.

Chapter 6. Comparing Seriation and Simulation

Even with relatively few initial environmental variables and very simplistic agent directives, the computer simulation of Rapa Nui prehistory becomes extremely complex. Exploring all possible combinations of variable values and simulation outcomes will require extensive future analysis. This chapter makes some general observations regarding environmental and population dynamics and also attempts to identify patterns of interest—specifically relating to calculations of energy investment in statuary derived in Chapter 4. Observations are made for the island as a whole but also in consideration of the possibility that the north and south experienced two distinct trajectories of cultural and ecological development.

Observations

Some variable dynamics are rather intuitive and require little explanation or intensive investigation. For example, as the initial timber value for each zone in the simulation decreases or the rate of deforestation increases, the island experiences forest loss more rapidly. Rapid deforestation leads to a relatively early stage of timber scarcity and consequent difficulty in accessing pelagic resources. The net effect of timber scarcity is an overall decrease in marine-resource productivity for all island cells. The precise timing and severity of deforestation may have a major impact (although indirect) in distinguishing the north from the south, and this point will be further discussed below.

The effects of other user-controlled variables in the simulation are more complicated, especially when differentiating their effects in the north from their effects in the south. Dividing the island between north and south based on Stevenson's (2002) work as discussed in Chapter 4, the north is composed of 1047 cells (approximately 94 km^2), and the south is composed of 794 cells (approximately 71 km^2). All other factors being equal, the north appears to have 1.3 times the inhabitable area of the south. However, all other factors are not likely to be equal. Islanders likely chose settlement locations based partly on access to marine resources, partly on proximity to arable land, and perhaps above all else on access to potable water. Although potable water resources may be distributed independently of marine or agricultural resources, the distance at which islanders were willing to live from potable water plays a major impact on the accessibility of marine and agricultural resources.

The spatial distribution of marine resources is determined by two user-defined variables in the simulation. First, the user may select the maximum slope or steepness (5, 10, or 15 degrees) of shoreline that islanders are able to traverse in order to directly access marine resources. Second, the user may also determine the distances at which islanders were willing or able to live from the coast and still benefit from marine resources. Determining the true maximum distance at which islanders were able or willing to live and still benefit from marine resources may be difficult. As the user restricts access to marine resources (either by reducing the maximum traversable slope of shoreline or by reducing the maximum cost-distance at which islanders benefit from

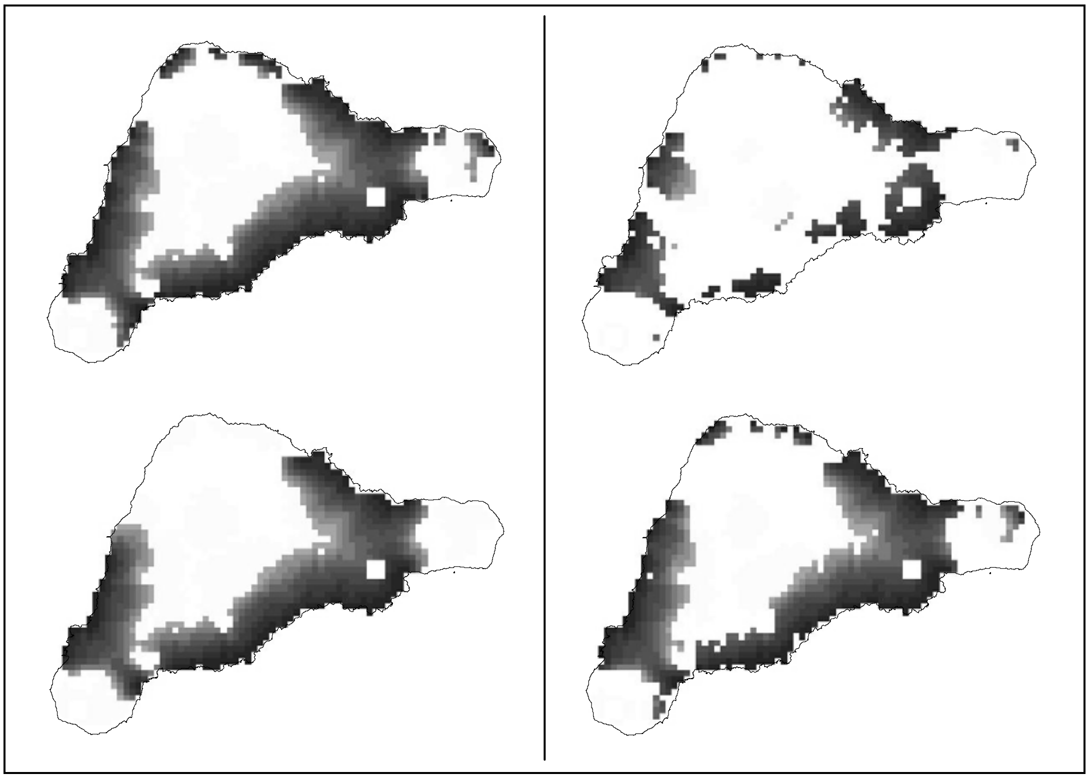


Figure 6.1. Images display the distribution of marine resources on the island (darker areas indicate more resources). Figures on the left demonstrate the differences when islanders are allowed to traverse steeper terrain to access coastline (above) and when islanders are only allowed to traverse mild slopes to access coastline (below). Figures on the right demonstrate the differences when islanders are forced to live in the immediate vicinity of potable water sources (above) and when islanders are allowed to live at greater distances from potable water sources (below). Restricting access to coastline and relaxing restrictions on access to potable water sources have a similar effect in that both increase the abundance of marine resources in the south relative to the north.

marine resources), the number of cells benefiting from marine resources in the south tends to increase relative to the north. Similarly, as the user allows islanders to live at greater distances from potable water sources, the number of cells benefiting from marine resources in the south tends to increase relative to the north. Figure 6.1 compares the spatial distribution of marine resources for simulations with varying restrictions on access to marine resources and access to potable water sources.

Islanders also depended on agricultural resources for survival. The spatial distribution of agricultural resources is determined by the user-defined productivities of various volcanic flows on the island, by rainfall (in turn related to elevation), and by the slope of the terrain. In determining the agricultural productivity of the north relative to the agricultural productivity of the south, it becomes necessary to understand which volcanic flows are of greatest impact, and what type of terrain (elevation and slope) characterize those flows of most importance. And again, the distance at which islanders were willing or able to live from potable water sources plays a significant role. In simulations where islanders lived only in close proximity to potable water sources, Table 6.1 suggests that there existed a major discrepancy between the north and south in terms of the number of cells pertaining to the Tangaroa (TA) and Hiva Hiva (HH) volcanic zones. Depending on the relative productivity of these flows and the terrain type that characterizes these flows, there may be a significant difference in agricultural productivity between the north and south of the island.

Table 6.1. Number of cells in each region representing distinct volcanic substrates when access to potable water is restricted severely.

	Number of Cells	
	North	South
HH	36	0
PO	4	0
RA	45	46
RK	9	9
TA	62	27
TE	14	7
TR	1	7
Total	171	96

Table 6.2 presents the number of cells pertaining to each volcanic flow in the north and south when spatial restrictions on access to potable water are relaxed. As the user allows islanders to live at greater distances from potable water sources, the greatest discrepancy between the north and south becomes the number of cells in the Hiva Hiva (HH), Poike (PO), Rano Aroi (RA), Terevaka (TE), and trachyte-rhyolite (TR) zones.

While the simulation may help to determine the relative productivity (both for marine resources and agricultural resources) of different zones on the island, absolute values for productivity or specific ratio values of productivity require further field research. Simulation results may help to guide and facilitate this research. For example, research on chemical composition or agricultural productivity may not be necessary for all volcanic flows, depending on our initial hypothesis. In making regional comparisons, only some of the volcanic flows may demonstrate significant discrepancies between the north and south (as in Tables 6.1 and 6.2).

Table 6.2 Number of cells in each region representing distinct volcanic substrates when restrictions on access to potable water are relaxed.

	Number of Cells	
	North	**South**
HH	62	0
PO	53	19
RA	148	236
RK	31	40
TA	209	208
TE	114	79
TR	2	31
Total	619	613

The simulation may also help to determine the general effects of spatial restrictions on access to potable water. Figure 6.2 suggests that the ratio of inhabitable cells in the north to inhabitable cells in the south approaches one as the maximum distance that islanders are willing to live from potable water approaches eight kilometers. Thus, as the spatial restriction on access to potable water is relaxed, the south may become increasingly productive and appealing to islanders. This phenomenon is due, in part, to the topographic form of the island. On average, cells in the northern region are characterized by an approximate slope of 4.8 degrees. Cells in the southern region of the island show an average slope of approximately 3.5 degrees. Therefore, as the simulation allows for islanders to live at greater cost-distances from potable water sources on a unit-by-unit basis, each unit increase often includes more zones or surface area in the south than in the north.

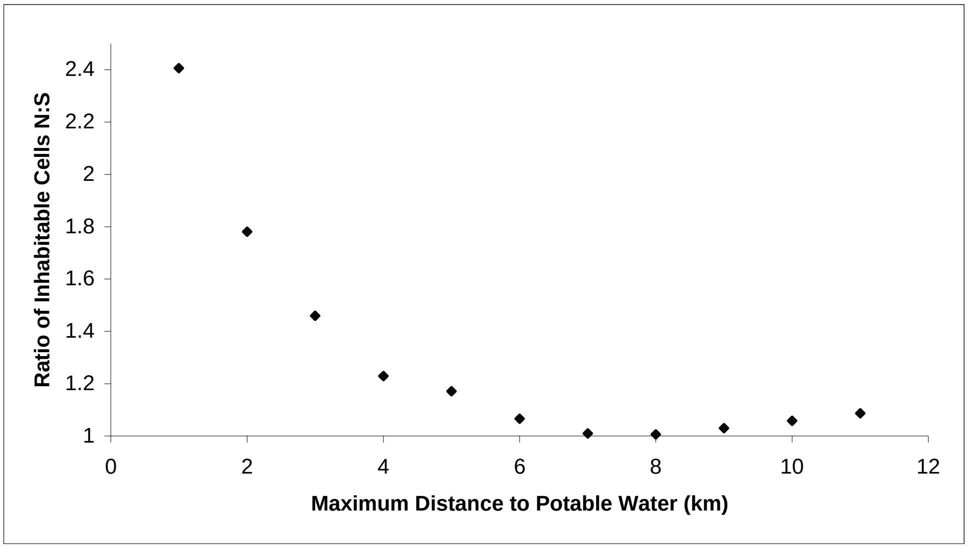


Figure 6.2. Ratio of inhabitable cells between northern and southern region based on different restrictions on access to potable water.

Determining precisely how close islanders lived to potable water sources may be a difficult task empirically. A detailed survey of settlement locations in relation to permanent fresh and brackish water sources may help to provide reasonable approximations for the average and maximum distances at which islanders were willing to live from water. Furthermore, this restriction may have even been one that changed over time. As prime locations (relative to potable water) became densely populated, islanders may have been forced to live at greater distances from water.

Simulation results concerning the habitability of cells based on access to potable water also help to indicate where there may be shortcomings in our understanding of potable water resources. One obvious example is on the northwest coast of the island in the Maitaki te Moa and Vai Mata regions (see Figure 6.3). Even when spatial

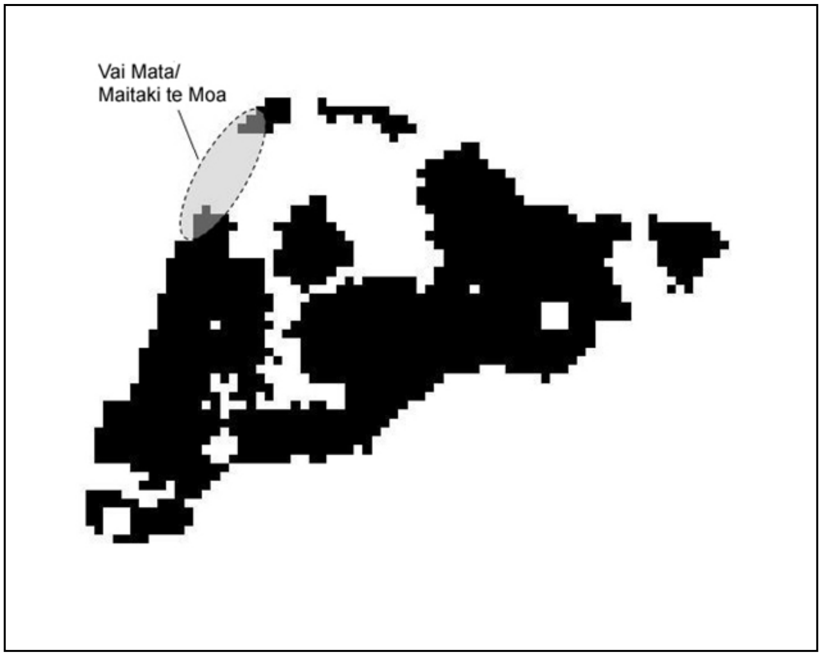


Figure 6.3. Distribution of cells with access to potable water (black) when spatial restrictions are relaxed. The Vai Mata/Maitaki te Moa region shows archaeological signs of habitation and ceremonial sites but in the simulation the region shows no access to potable water.

restrictions on access to water are relaxed, this region appears to be uninhabitable in the simulation. However, both regions contain abundant archaeological remains (both ceremonial and residential). This may suggest that natural fresh/brackish water sources in this area have been underreported. There is also the possibility, however, that a number of large *taheta* (carved stone rainwater catchment troughs) in this area provided ample potable water to support a local population (Morrison, personal communication). Again, further detailed field research may help to expand our understanding of water resources on the northwest coast as well as other specific regions of the island. Overall, the simulation serves to demonstrate the relative importance, among other environmental factors, that potable water resources and island topography may have played in shaping Rapa Nui cultural prehistory. In the past, these ecological factors have received relatively little attention from archaeologists compared to archaeological remains themselves.

Spatio-Temporal Patterns

The observations of simulation results discussed in the previous section are almost entirely spatially-oriented. However, one of the advantages of a computer simulation approach to archaeological analysis is that spatial and temporal phenomena can be analyzed simultaneously. Specifically, the simulation analysis discussed here attempts to identify patterns that may relate to, corroborate, or help to explain those calculations derived in Chapter 4 for energy investment in monumental statuary for different regions of the island during different time periods.

Figure 6.4 exhibits the temporal distribution of statue manufacture events in the north and south as well as the corresponding calculations for energy investment in statuary over the centuries. As discussed in Chapter 4, these figures are corroborated to some extent by research settlement pattern studies and chronometric dating of other forms of monumental architecture. Nevertheless, the optimal path seriation results that form the chronological ordering of statues from which Figure 6.4 was derived must still be regarded as preliminary and hypothetical. Computer simulation offers one opportunity to reject the hypothesized chronological ordering of statues if, under reasonable starting conditions and agent directives, no pattern emerges that correlates to those patterns in Figure 6.4.

Perhaps most noticeable in Figure 6.4 is the difference between the temporal trajectories of the north and south, both in terms of the numbers of statues constructed and the amount of energy invested in statuary. The north seems to experience a relatively early (13^{th} century) and small peak in both the number of statues constructed and the amount of energy invested. After a temporary decrease, the north seems to experience a possible second peak in energy investment around the 15^{th} century. In the south, however, statue construction and energy investment remain at relatively low levels until the 14^{th} century, then come to a peak in the 15^{th} and 16^{th} centuries, and then subside.

The different variables and numerous variable values in the simulation create such a large variable-space that identifying a combination of variables that produces a pattern related to those patterns of energy investment in statuary can be extremely difficult. Identifying patterns of interest may depend on the robustness of the results that form the pattern of interest. In other words, those results for which a number of different combinations of variable values produce similar patterns may be the easiest to identify. In this analysis, preliminary investigations of the simulation variable-space based initial conditions for variables on either absolute or relative values suggested in previous archaeological and paleoenvironmental research.

Depending on the user-defined variable values regarding potable water, marine resources, and agricultural resources, the northern and southern regions of the island may offer extremely different levels of productivity and habitability. However, early testing of the simulation revealed that despite the different environmental conditions in the north and south, population dynamics are relatively similar throughout the island. As soon as one particular region of the island begins to experience rapid population growth and even

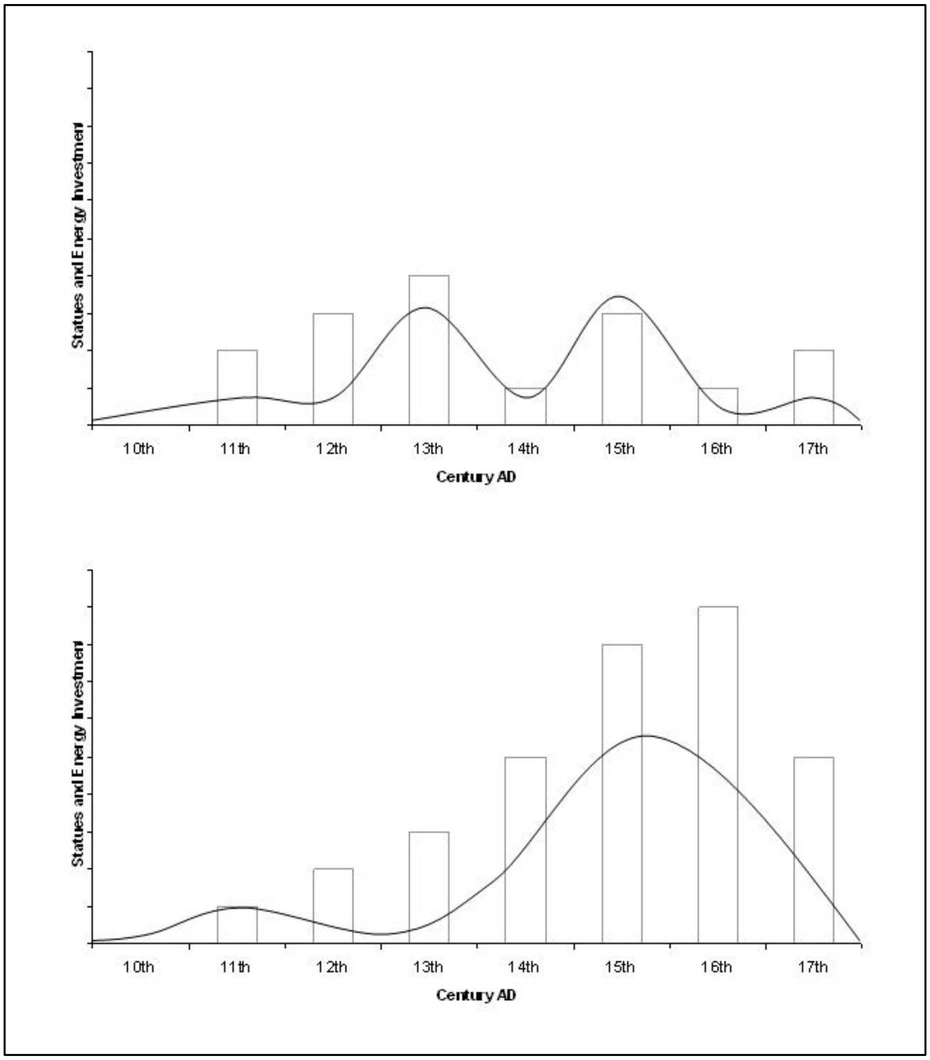


Figure 6.4. Calculations for the number of statues constructed (bars) and energy invested in statuary (lines) based on the statue chronology derived from the optimal path seriation analysis in Chapters 3 and 4. Calculations vary considerably between the north (top) and south (bottom).

minor stress on resources, islanders tend to disperse from that region. The mobility of the islanders leads to a rapid equilibrating effect across the island so that the population-to-carrying-capacity ratio is roughly the same for all regions of the island at all times. This sort of spatial uniformity over time offers little explanation or support for the differential energy investment trajectories hypothesized for the northern and southern regions of the island.

The simulation can, however, produce very different results with a slight modification in agent directives. If the simulation imposes impermeable spatial boundaries on agents, new and unique patterns emerge for different regions of the island quite readily. Specifically, the simulation was modified so that the initial colonizing population is distributed randomly about the island landscape in cells with access to potable water sources. As time progresses, islanders move about the landscape in search of resources as necessity requires. However, islanders are only allowed to move to other cells in the simulation that pertain to the same region (north/south) in which the islander currently resides. In other words, those islanders that are initially located in the north (and subsequent generations of offspring) will stay in the north, and those islanders that are initially located in the south will stay in the south.

Explicit references to the historic sociopolitical division between north and south on the island were discussed in Chapter 4. In the simulation, this boundary is made impermeable, but the simulation may also evolve different culture histories for the north and south when the boundary is only semi-permeable. Future simulations for Rapa Nui, or even more generalized cases, may help to determine the regional differences that may accumulate as a result of varying degrees of permeability for territorial boundaries.

Initial investigation of the simulation variable-space, when mobility between the north and south is prohibited, identified a recurring pattern that may correlate to hypothesized patterns of energy investment in statuary. The simulation produces a pattern where extended episodes for which the regional (north or south) population is pushing the limits of, or even surpassing, the regional carrying capacity may correspond to peaks in energy investment in statuary from Figure 6.4.

The anthropological notion of carrying capacity is complicated and often debated (Glassow 1978). Kirch (1984:103) defines the carrying capacity as, "the density of individuals at which the population ceases to grow." Carrying capacity, in the following discussion, refers to a specific maximum sustainable population value (computed yearly) in the computer simulation, given short-term and long-term ecological conditions as well as technology. Although this implementation of the concept of carrying capacity may not be empirically sufficient for physical archaeological studies, the simplicity and controlled nature of the simulation analysis allows for its meaningful application in this analysis.

Figure 6.5 displays the population and carrying capacity dynamics for the northern and southern regions of the island from an actual simulation. Although one of the advantages of computer simulation is that it produces a continuous sequence of events through which the user can observe variation, these events are divided into six distinct phases for the sake of discussion (see Table 6.3). These phases are developed with reference to the simulation rather than direct archaeological evidence but appear to show correlations to previous archaeological syntheses.

Phase 1 (AD 900 – 1150) may correspond to what previous studies have identified as a time of initial settlement (Ayers 1975; Kirch 1984; Lee 1986; Stevenson

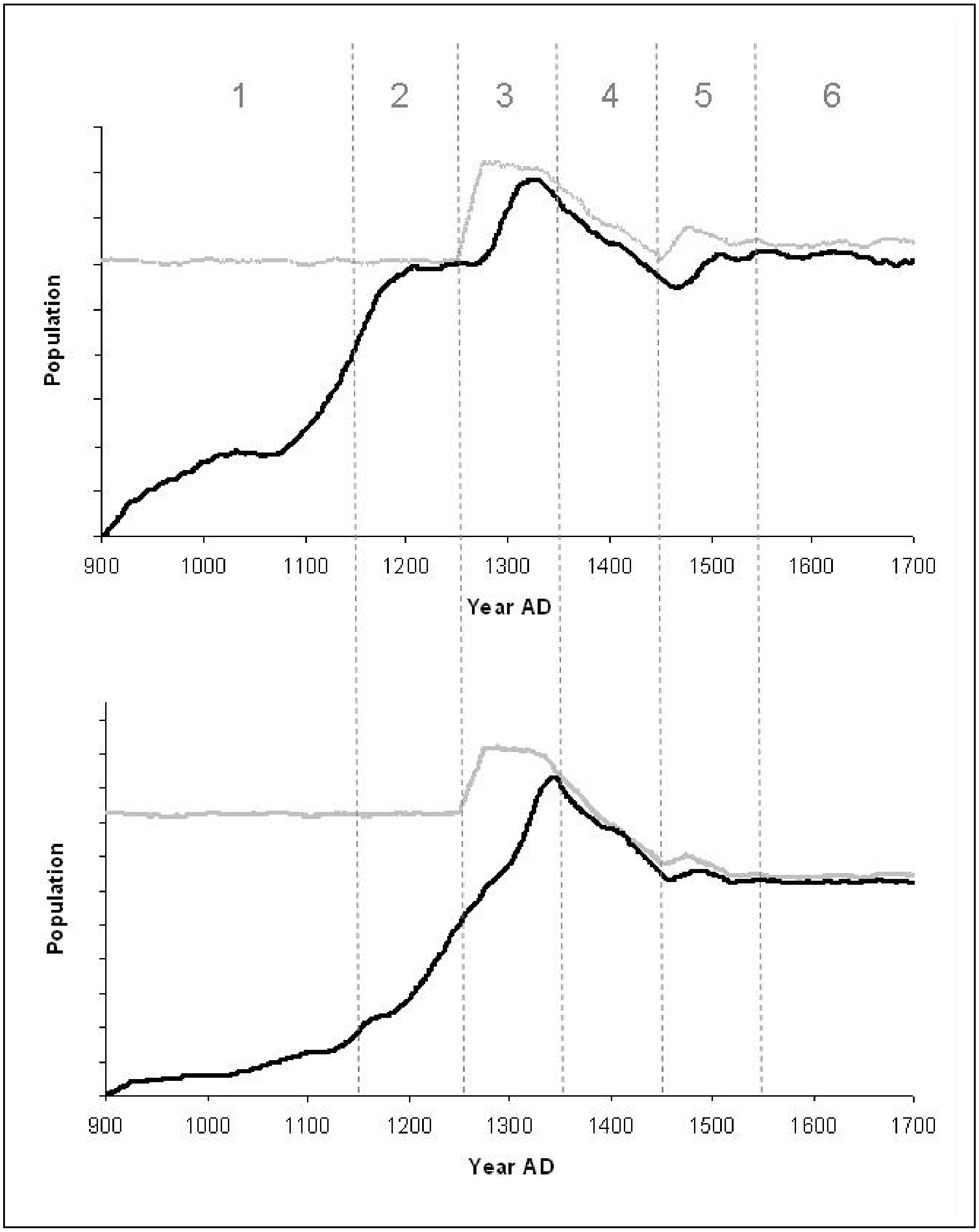
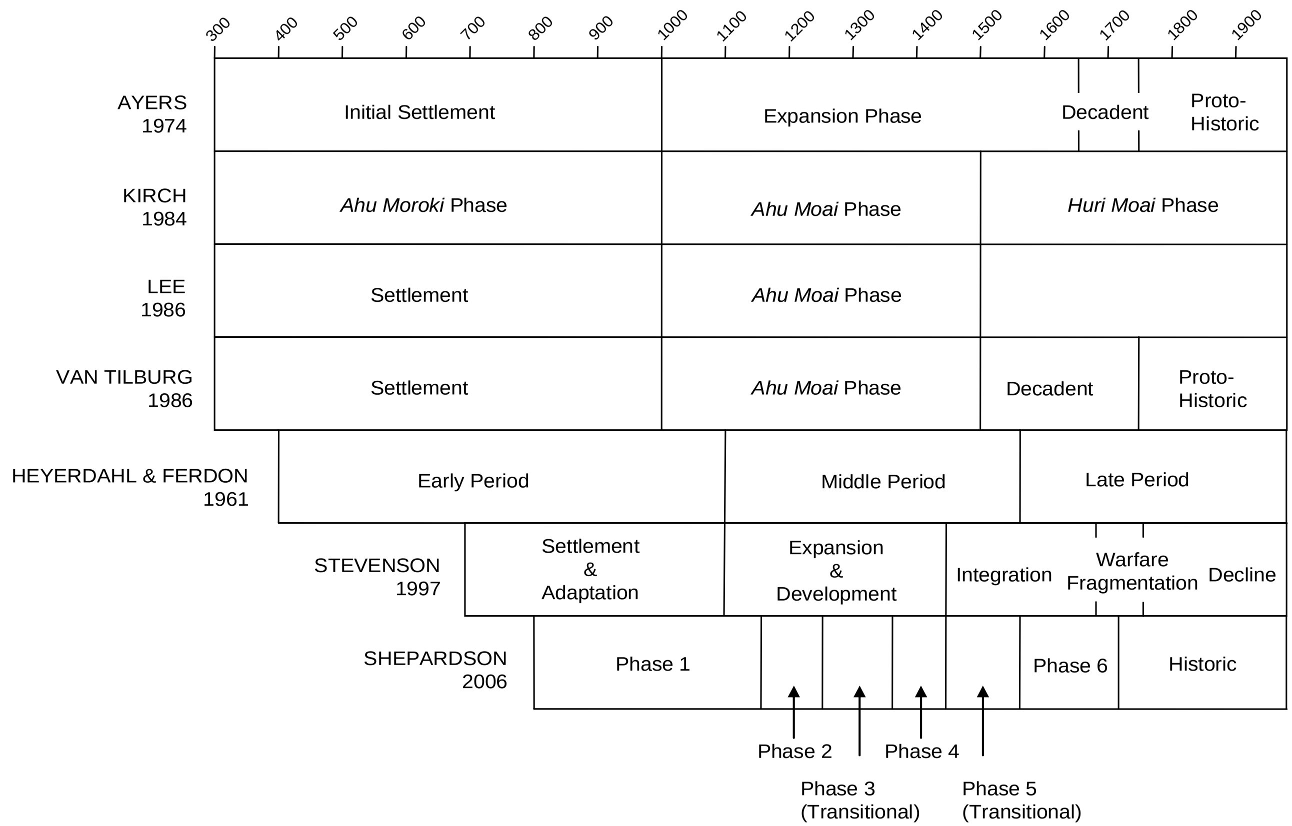


Figure 6.5. Computer simulation results calculating the regional carrying capacity (grey) and population growth (black). Results for both the northern region (top) and southern region (bottom) have been divided into six distinct phases for discussion.

Table 6.3. Comparison of cultural chronologies.



1997; Van Tilburg 1986). During this time, islanders settled the island (at AD 900 in the simulation) and established a limited number of traditional Polynesian plant and animal domesticates. In the simulation, populations begin to grow, but remain well below their respective regional carrying capacities.

By Phase 2 (AD 1150 – 1250) of the simulation, islanders continue to seek out areas of the island that may offer ample resources. The regional populations continue to grow, but the population in the northern region may have begun to experience serious environmental pressures due to a relatively low carrying capacity. The population in the south, on the other hand, remains well below a significantly greater regional carrying capacity.

Phase 3 (AD 1250 – 1350) of the simulation marks a transitional increase in the carrying capacity for both the north and the south. Sometime after AD 1200, both the north and the south benefit from the development of new agricultural technologies. Lithic and vegetative mulching may have been two of the technological advances that increased agricultural productivity (and the carrying capacity) in both regions. The increase in carrying capacity may have offered a respite from environmental pressures for the population in the northern region. In the south, changes in agricultural technology may have simply delayed the convergence of population and carrying capacity.

In Phase 4 (AD 1350 – 1450), after temporary relief from environmental pressures, the northern population grows to approach the regional carrying capacity again. The southern population has also reached a point where regional environmental conditions may have regularly stressed the population.

Phase 5 (AD 1450 – 1550) in the simulation is another transitional point for environmental conditions on the island. The sweet potato is introduced to the island early in the 15th century, and as a result, potential agricultural productivity increases rapidly. Around the same time, deforestation reaches devastating levels on the island, and access to pelagic resources is severely restricted by AD 1450. The contemporaneous increase in carrying capacity due to the introduction of sweet potato as a staple crop and decrease in carrying capacity due to deforestation and inaccessibility of pelagic marine resources may have had different effects regionally on the island. The population in the southern region, which had previously benefited from greater access to and dependence on pelagic resources, experiences almost no net increase (or possibly a small decrease) in regional carrying capacity. The population in the northern region, conversely, which previously exploited marine and agricultural resources roughly evenly, may have experienced a significant net increase in regional carrying capacity. Consequently, the population in the northern region may have again enjoyed a brief respite from environmental pressures. The population in the southern region, at the same time, persists at high levels relative to the regional carrying capacity.

Phase 6 lasts until AD 1700, shortly before the first instance of European contact. During the final simulation phase, the regional populations both reach extremely high levels relative to their respective carrying capacity. Furthermore, in the simulation, whereas the southern region initially had a greater carrying capacity than the northern region, the regional carrying capacities are roughly equal during Phase 6.

Figure 6.6 superimposes hypothesized regional energy investment levels in statuary on graphs depicting regional population and carrying capacity dynamics. Energy investment in statuary in the north appears to peak toward the end of Phase 2 and again toward the end of Phase 4. Similarly, those periods for which energy investment in statuary is actually decreasing in the northern region may be concurrent with the transitional periods of Phases 3 and 5, where the population-to-carrying-capacity ratio is temporarily reduced in the north. In the south, energy investment in statuary grows to high levels in Phase 3 and 4 and peaks in Phase 5. In both regions, energy investment in statuary appears to correspond to, or closely follow, periods for which the regional population-to-carrying-capacity ratio is sustained at high levels (see Figure 6.7). As the population-to-carrying-capacity ratio declines, so does energy investment in statuary.

Although both regions display a high population-to-carrying-capacity ratio during Phase 6, the decline or lack of energy investment in statuary may not be surprising. Several studies have suggested that during the 16^{th} and 17^{th} centuries, statuary may have been abandoned as a result of endemic warfare, ecological catastrophe, or simply in favor of alternative forms of cultural elaboration (see Bahn and Flenley 1992; Diamond 1995, 2005; Heyerdahl and Ferdon 1961; Kirch 1984; Lee 1986; Van Tilburg 1986; Wright 2004).

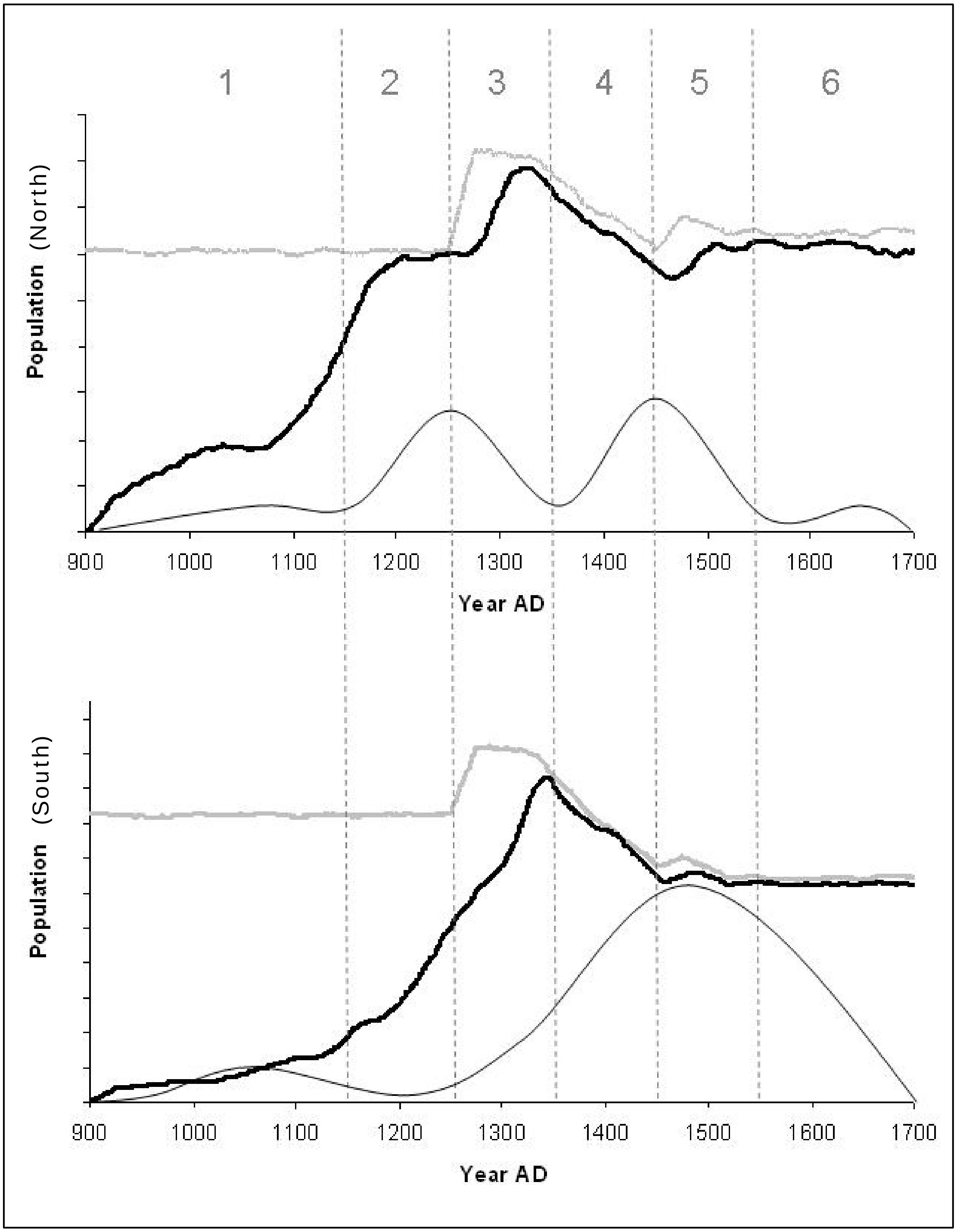


Figure 6.6. Comparison of ecological and population dynamics from computer simulation to energy investment calculations from the optimal path seriation analysis for the northern (top) and southern (bottom) regions of the island. Heavy grey line indicates carrying capacity; heavy black line indicates population; and smooth grey line indicates energy investment.

Comparing Chronologies

While this study divides the time between initial colonization and European contact into six distinct phases based on simulation results, prior syntheses of Rapa Nui prehistory have generally divided the same span of time into just three phases (see Ayres 1975; Heyerdahl and Ferdon 1961; Kirch 1984; Lee 1986; Van Tilburg 1986). This does not necessarily indicate that prior analyses *differ* qualitatively in the interpretation of prehistoric events or trends from those identified by computer simulation. Phases 1, 4, and 6 from the simulation analysis all present periods in which different regions of the island were characterized by similar population and environmental dynamics. In a sense, these phases allow us to make island-wide generalizations, and may justify or account for the tri-partite sequence offered in previous analyses. The computer simulation may effectively intersperse Phases 2, 3, and 5 to account for spatial variability and the transitional episodes associated with changes in technology or access to resources.

These transitional periods reflect changes in technologies or resources that impacted productivity and carrying capacity. And while these transitional periods assume precise periods of time within the simulation, actual transitions may have occurred at slightly different times in Rapa Nui prehistory and blended with other phases. The importance of simulation results is to demonstrate the effects of complex interactions between humans and resources, not to reenact Rapa Nui prehistory in faithful detail.

The regional division between north and south in this analysis demonstrates that although the island is relatively small, spatial variability in access to (or dependence on) different types of food resources may have led to different ecological conditions across

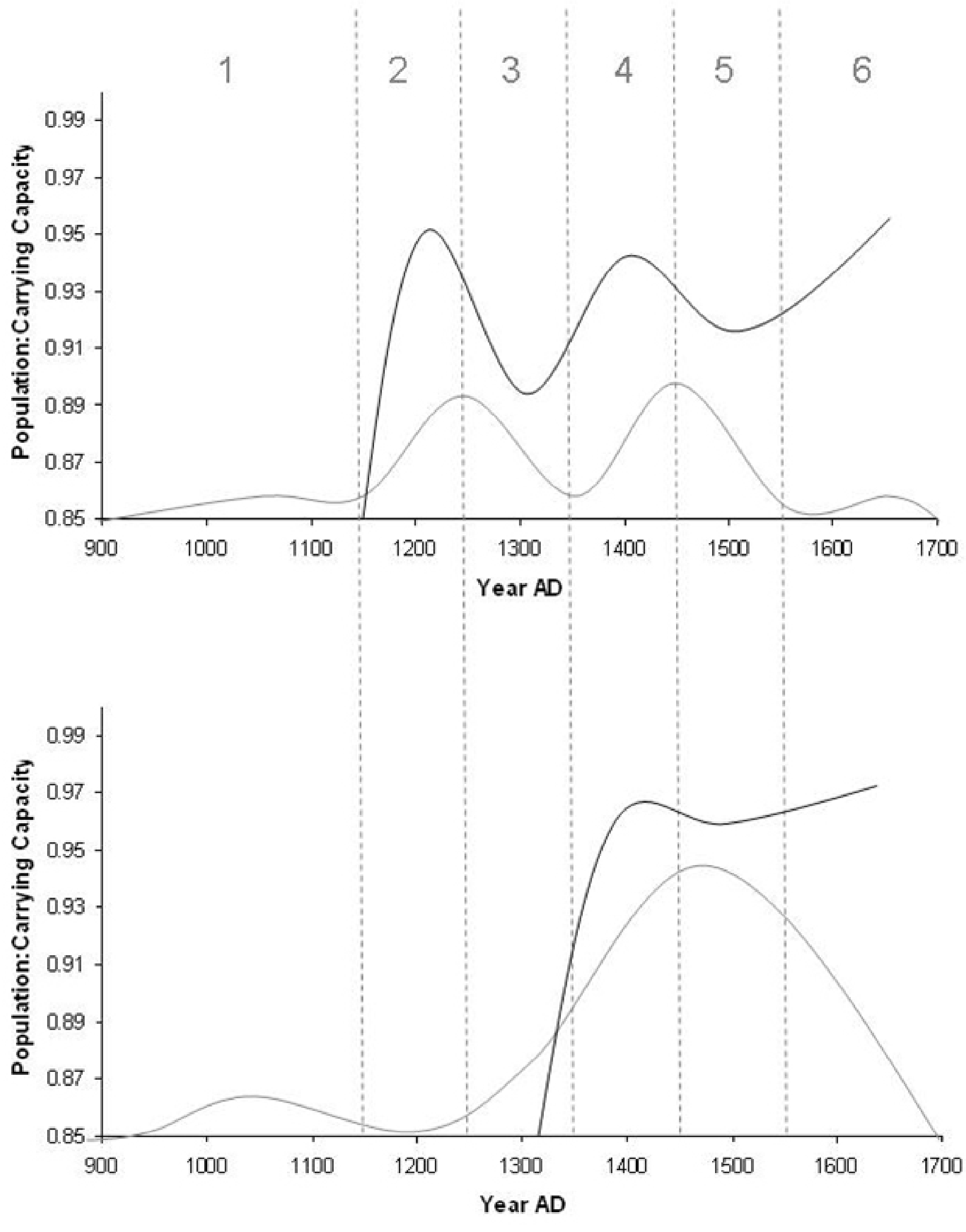


Figure 6.7. Comparison of energy investment calculations (grey) to population-to-carrying-capacity ratio (black). The northern region (top) appears to show two distinct small peaks while the south (bottom) shows one late, large peak. Despite potentially high population-to-carrying-capacity ratios in Phase 6, statue production declined across the island.

the landscape. This phenomenon may also demonstrate the importance in recognizing spatial variability rather than attempting to summarize cultural and ecological dynamics for the entire island in one simple chronology.

By including the two transitional phases in the cultural chronology, a new level of complexity is also added to the chronology of energy investment in statuary. The events (deforestation, advances in agricultural technology, introduction of sweet potato) that may lead to transitional phases occur at specific time periods within the simulation. However, the chronology within the simulation may be of less importance than the relative timing and/or interaction of separate events. Regional carrying capacity dynamics during the two transitional phases help to define the relationship between energy investment in statuary and the regional population-to-carrying-capacity ratio. As a result, construction of statues no longer appears to be a simple function of time, productivity, or cultural progress as has been suggested previously (e.g., Bahn and Flenley 1992; Diamond 1995; Kirch 1984; Sahlins 1958).

Furthermore, while previous studies have implied that an intense dedication toward the construction of monumental statues may have been partially responsible for severe ecological and demographic collapse on the island, the simulation results present an alternative scenario for consideration. Kirch (1984) discusses different possible trajectories of population growth (e.g., extinction, exponential, logistic, overshoot or crash, oscillating, and step) on Polynesian islands. Quite commonly, Rapa Nui has been cited as a prototypical example of the "overshoot" or "crash" model of population growth in which "population levels climb well above carrying capacity, and having exceeded their resources base, undergo a subsequent crash" (see Figure 6.8 adapted from Kirch 1984:103).

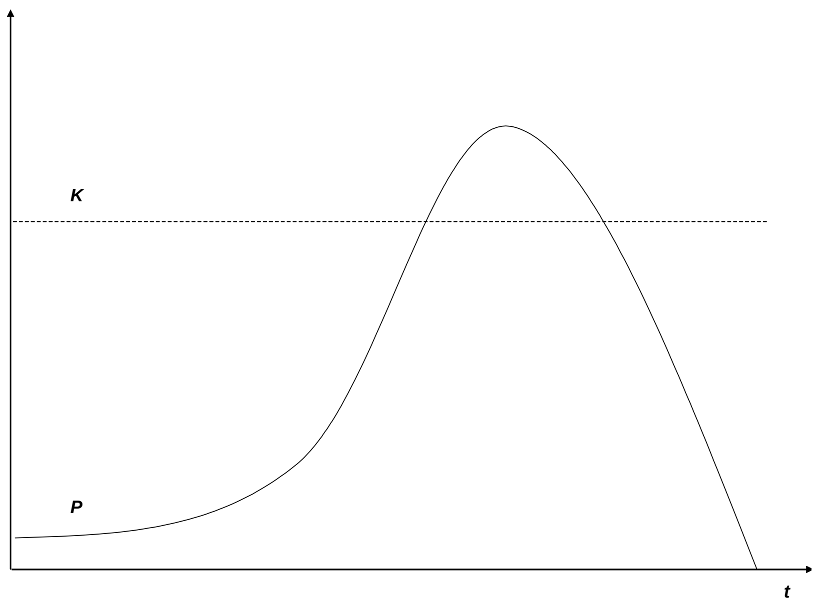


Figure 6.8. Population growth and decline in the "overshoot" or "crash" model.

However, examination of demographic trends in the computer simulation suggests that an alternative generalization of population growth on Rapa Nui might more closely reflect the "logistic" trajectory for the southern region and the "step" trajectory for the northern region (see Figures 6.9 and 6.10). As Meyer (1994:89) states,

> The logistic law of growth assumes that systems grow exponentially until an upper limit or 'carrying capacity' in the system is approached, at which point the growth rate slows and eventually saturates, producing the characteristic S-shape curve.

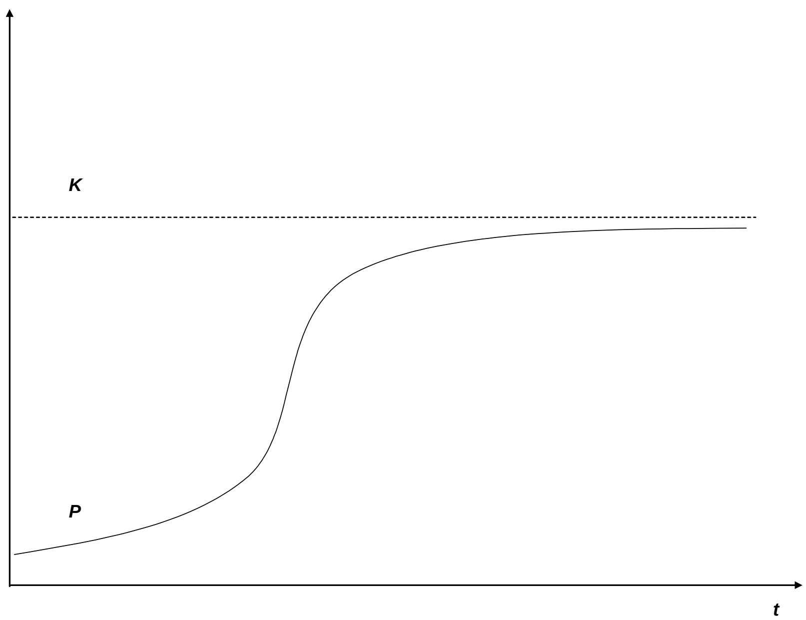


Figure 6.9. Population growth in the “logistic” model.

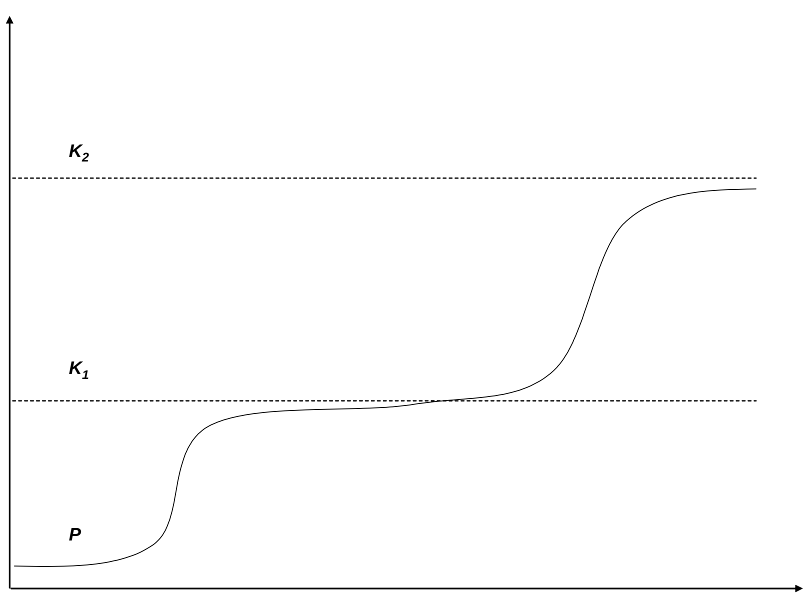


Figure 6.10. Population growth in the “logistic” model.

The “step” pattern is also explained more explicitly by Meyer (1994:89),

> The carrying capacity of a human system is often limited by the current level of technology, which is subject to change. More generally, species can sometimes alter and expand their niche. If the carrying capacity of a system changes during a period of logistic growth, a second period of logistic growth with a different carrying capacity can superimpose on the first growth pulse…We call such a system with two logistic growth pulses, growing at the same time or sequentially, “Bi-Logistic”.

While the northern region of the island may actually experience “Tri-Logistic” growth in the simulation, the principles are the same as those discussed by Meyer. At a finer scale, the simulation may demonstrate an “oscillating” phenomenon for those time periods in which the regional population reaches the carrying capacity (see Figure 6.11). Kirch (1984:103) explains that in the oscillating trajectory, “the overshoot and crash are less pronounced [than in the crash model], and population levels oscillate around carrying capacity.” Furthermore, the carrying capacity might experience minor changes to which the population is forced to react and adjust.

In other words, upon reaching or briefly surpassing the local carrying capacity, the population may quickly adapt to severe environmental pressures and a high population-to-carrying-capacity ratio. In light of the hypothesized correlation between energy investment in statuary and extended episodes in which the population approaches, oscillates about, or adapts to the regional carrying capacity, the simulation analysis may postulate as Hunt and Lipo (2003:108) did, “In short, the construction of stone

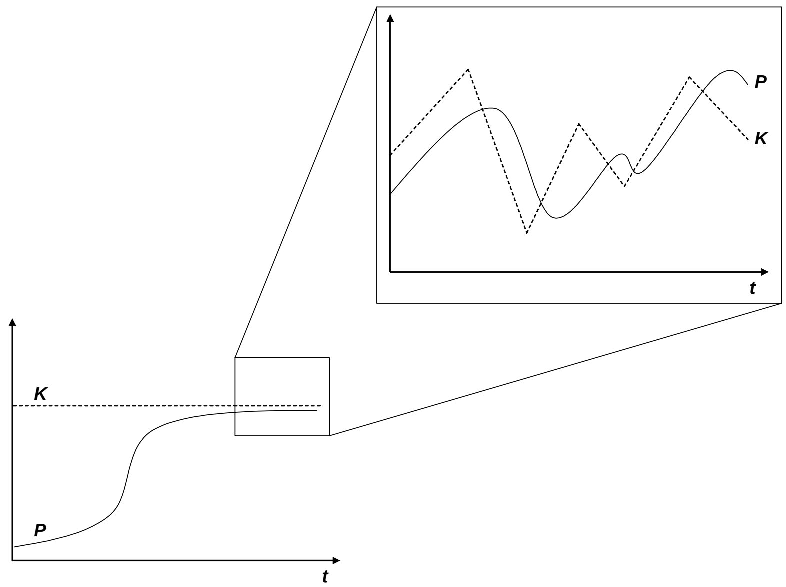


Figure 6.11. Population growth and decline in an "oscillation" model.

monuments did not cause the destruction of the island's population and culture, but may well have fostered their persistence." The following chapter discusses the results from the seriation analysis and computer simulation in the context of long-standing and more recent theoretical explanations for cultural elaboration and monumentality on Rapa Nui and elsewhere in the Pacific.

Discussion

Computer simulation presents one important method by which the statue chronology and calculations for energy investment in statuary derived from the optimal path seriation analysis presented in Chapters 3 and 4 can be tested, and in this case corroborated. There appears to be a positive correlation between elevated levels of energy investment in statuary and elevated population levels relative to the regional carrying capacity. This relationship and its implications are discussed more thoroughly in Chapter 7.

Specific simulation parameters that produce demographic patterns corresponding to hypothesized calculations for energy investment in statuary also produce a general cultural chronology for Rapa Nui that shows similarities to previously published cultural chronologies.

Together, the optimal path seriation analysis and computer simulation testing yield a prehistoric sequence that can be divided into six distinct temporal phases and still account for potential geographic variability between the north and south of the island. The first, fourth, and sixth phases may present general similarities to the traditional three-part cultural chronology cited so commonly in Rapa Nui studies. However, the second and fifth phases highlight episodes in which the island may have undergone transitions in terms of resources, technology, and carrying capacity. These transitional phases may represent relatively brief spans of time, but they may be critical in the island's prehistory in order to explain and understand why the island culture shifted from each one of the three traditionally cited phases to the next.

Determining the robustness, or likelihood, of the simulation results is an important task for future research. While robustness can be assessed statistically, even for the described simulation, the assessment depends heavily on what current and future investigations regarding Rapa Nui's paleoenvironment hold to be "reasonable" conditions.

However, even if simulation results are not particularly robust, the method has already demonstrated a capacity to assess new hypotheses and situate these hypotheses and their implications in the context of long-standing archaeological explanations. Furthermore, the particular simulation presented in this chapter identifies several key variables that have not yet played major roles in accounting for the culture history or cultural evolution of Rapa Nui.

While deforestation has been a topic central to archaeological and paleoenvironmental studies, its impact on access to pelagic resources is not often explored in an explicit or systematic quantitative manner (but see Brander and Taylor 1998 for example). Similarly, only recently have archaeologists begun to document and critically evaluate developments in agricultural technology on Rapa Nui (e.g. Ladefoged et al. 2005; Stevenson et al. 1999; Stevenson et al. 2002; Wozniak 1998, 1999, 2001, 2003). Computer simulation builds on recent research regarding agricultural technology and directly links deforestation to pelagic resources to demonstrate the island-wide and even unique regional impacts that these topics may have had in prehistoric Rapa Nui.

The simulation also demonstrates the important role that access to fresh water resources may have played on the island, and consequently, how important this topic will be in future archaeological or paleoenvironmental investigations. Fresh water resources, in conjunction with agricultural and marine resources, become critical in assessing spatial variability in the relative habitability or productivity of different regions on the island.

Chapter 7 addresses simulation results based on a current understanding of spatial and temporal environmental productivity in order to discuss the relationship between environmental productivity, population demographics, and energy investment in megalithic statuary.

CHAPTER 7. LIMITATIONS, IMPLICATIONS, AND CONCLUSIONS

The methods, analyses, and interpretations within this study present several limitations. Some of the difficulties or weaknesses may be improved with further research, yet others may be inherent to the methods employed in archaeological investigation. Chronological analysis of statuary, along with estimates for energy investment in the construction, transportation, and erection of statuary are based on a 712-statue database collected over the course of ten months in 2003, 2004, and 2005.

This database, while extensive, is incomplete. Furthermore, the prospect of acquiring a complete database of all statuary carved prehistorically is bleak. Statues have been shipped to foreign countries, claimed as personal property on the island, buried through natural weathering, and eroded to a sometimes unrecognizable state. Without a complete database for reference, determining whether the 712-statue database accurately represents all regions of the island or all points during statue manufacturing becomes difficult. Future survey work may identify additional statues to include in the database.

Unfortunately there are also limitations in accuracy with which formal dimensions of statues can be measured. Severe erosion to statues often reduces corners to curves, and may blur the boundaries of formal variables on statues. Some of the best-preserved statues, on the other hand, are either partially buried or rest in otherwise precarious positions such that particular formal dimensions were inaccessible for measurement. Statues that remain erected in the quarry region or re-erected on reconstructed *ahu* around the coast may require scaffolding or photogrammetry in order to accurately measure statues without harming them in the process. Some erected statues, however, are accounted for in this study. Archived data from the Padre Sebastián Englert Anthropological Museum on Rapa Nui provided formal measurements for thirty statues (Riquelme et al. 1991).

Ultimately, errors in measurement and sampling may affect results for the seriation analysis and estimates of energy investment in statuary. Optimal path seriation also has limitations that may be ingrained in the method of seriation. Seriation is an archaeological method with limited applicability—easily conflating variability attributable to time with variability attributable to space. Traditionally, object-scale seriations have offered only relative orderings of artifacts. Optimal path seriation incorporates chronometric information from other dating techniques performed on contextual materials from ceremonial statue sites. These dates may offer greater accuracy in the seriation analysis, but subject the results to potential errors or oversights in those projects that initially generated chronometric dates.

Estimating energy investment in statuary depends on the ability to accurately measure statue mass (or at least volume) and transport routes used to move statues from the quarry area to their respective destinations. Measuring statue mass (or volume) presents potential difficulties already discussed in relation to data collection. While several statue transport routes have been identified (see Lipo and Hunt 2005; Routledge 1919; Shepardson 2005a), they are not necessarily the only routes that were used or routes that were always used. Estimates for transport costs in this study were based on the easiest paths traversable between the quarry location and statue locations. This approach may systematically underestimate actual transport costs but maintains objectivity in the analysis.

Much of the analysis regarding estimates of energy investment in statuary draws upon a geographic distinction between the northern and southern regions of the island. Several previous studies have referred to the same geographic distinction, either explicitly or implicitly (e.g., Graves and Sweeney 1993; McCall 1979; Stevenson 1986, 2002; Stevenson et al. 2002). At the same time, however, there is little archaeological evidence to place this division in a precise geographic location on the island or for a specific span of time. The north/south distinction is employed in this study to address the significant differences observed in regional energy investment in statuary.

It is important to remember that while this study attempts to formulate conclusions or explanations regarding the persistence and variability of energy investment in monumental constructions, statuary is only one type of monument on Rapa Nui. Future studies may address energy investment in *ahu* (ceremonial altars), *hare paenga* (boat-shaped houses), and other forms of monuments in order to form a more comprehensive or holistic picture. The methods employed here to study statuary may, in future research, provide a model for research on other forms of monumental construction on Rapa Nui and elsewhere in the Pacific.

Finally, the simulation component of this research also presents limitations. Paleoenvironmental research is constantly changing our understanding of prehistoric conditions on Rapa Nui. Thus, initial conditions and resource dynamics within the simulation will need to be updated periodically. These updates may change the simulation results, but by programming in an object-oriented manner (so that each process or resource is represented by a distinct block of computer code), the overall structure of the simulation will not necessarily have to change. Simulation also raises concerns with the significance of results. Even relatively simple models are capable of producing a wide-variety of results. This does not imply that all results are without meaning—only that as an analytical tool, simulation must be utilized with caution.

As with any archaeological investigation, data is bound to improve in the future (with respect to statue chronology and paleoenvironmental parameters) and analytical results will change. Yet, despite the drawbacks of the data and methods employed in this research, the seriation and simulation analyses present a quantitative and systematic approach to the study of statuary and prehistoric cultural elaboration. Furthermore, this approach produces detailed results for both cultural and environmental processes that can then be interpreted to assess the potential of existing explanatory models.

In the last four to five decades, research regarding prehistoric monuments in Polynesia has been dominated by a cultural evolutionary approach. Only in the last two decades have archaeologists begun to frame research in a more scientific manner. The following discussion considers the differing frameworks, their expectations, and their success in accounting for patterns observed through the seriation and simulation analyses in this research.

A Cultural Evolutionary Framework

In cultural evolutionary studies in the Pacific, monumental (or ceremonial or religious) architecture has been closely associated with sociopolitical complexity and status hierarchies (Sahlins 1958). Even amongst the earliest, most influential cultural evolutionary anthropologists, there were different opinions as to how status hierarchies and social complexity develop.

Sahlins (1958), building upon the work of Leslie White (1949), reasoned that sociopolitical complexity was a reflection of the efficiency by which a group was able to harness energy from the surrounding environment. Thus, to Sahlins, sociopolitical organization was a function of both technology and environmental productivity.

Goldman (1955, 1970), on the other hand, in a Marxist-like framework, attributed increases in sociopolitical complexity to the pressures of status rivalry. According to Goldman, status rivalry eventually pushed societies through three increasing types of sociopolitical complexity: Traditional, Open, and Stratified. Fried (1967), similarly, stressed status rivalry as leaders competed for power to ensure access to critical resources.

Regardless of the mechanism by which cultural evolutionary interpretations explain the emergence of sociopolitical complexity, they share a common functionalist ideal. In general, cultural evolutionary studies suggest that social hierarchies, religion, and ceremonial architecture (amongst other societal institutions) operate in a complementary fashion and grow or progress in proportion to one another. The unifying variable in cross-cultural studies became environmental diversity or productivity

(Goldman 1960; Sahlins 1958). Thus, in Polynesia, different island cultures are assumed to stem from a "single cultural genus" and progress to new types of social complexity to fulfill the potential of the surrounding environmental productivity (Graves and Ladefoged 1995:158; Graves and Sweeney 1993).

Therefore, cultural evolutionary studies imply that monumental architecture, being directly related to social organization, religion, and ultimately environmental productivity, is expected to appear first in the most productive or fertile regions and increase over time (with advances in technology or sustained pressure through status rivalry). This expectation was made explicit early on by Suggs (1961) in archaeological investigations of the Marquesas but also more recently in other regions of Polynesia.

Kirch applies cultural evolutionary expectations for monumental architecture to Molokaʻi (1990) and Oʻahu (1992), suggesting that the location and intensity of ceremonial architecture is directly related to areas with enhanced productivity due to fishponds or irrigation. Kolb (1991) proposes the same for Maui, and Peebles and Kus (1977) make a similar broad generalization for the entire Hawaiian archipelago.

Stevenson (1986) offers a progressivist model for Rapa Nui as well, specifically referring to the southern region of the island. He posits that construction of ceremonial architecture in the form of *ahu* (platforms) is linked to increases in population and productivity in the most powerful or successful social groups.

Given the current understanding of Rapa Nui's paleoenvironment, or at least the conditions set forth in the computer simulation based on current available paleoenvironmental research, specific cultural evolutionary expectations can be derived for the temporal and spatial distribution of monumental architecture or statuary on the island. The southern region, offering the highest combined productivity levels for marine and agricultural resources, is expected to host the earliest monuments and then show a steady increase in monuments over time with corresponding increases in population and technology. The northern region, characterized by a less productive environment, may show reduced levels of energy investment in monumental architecture or statuary that begin relatively late in Rapa Nui prehistory.

Energy investment in prehistoric statuary on Rapa Nui and paleoecological reconstruction in the preceding simulation analyses do not appear to conform to the expectations of a cultural evolutionary framework. While energy investment in statuary does appear to grow steadily to a peak in the southern region, the early onset of energy investment in statuary in the south is relatively small compared to the northern region. The southern region does not experience high levels of energy investment in statuary until later in the chronology.

Furthermore, the northern region shows two peaks in energy investment in statuary rather than any continual growth that is expected to correlate with population size, productivity, or social complexity. And rather than a later onset or increase of monuments in the northern region, there appears to be a relatively high investment in the northern region *before* equivalent levels of energy investment in the southern region.

Despite the poor fit to cultural evolutionary expectations, the temporal trajectory of steady growth in energy investment in statuary for the southern region may help to explain why the cultural evolutionary approach has been so popular for Rapa Nui. Considering that approximately 82% (581 out of 712) of surveyed statues reside in the southern region, temporal trends in statuary for the southern region may overwhelm spatial variability or temporal variability outside of the southern region in holistic syntheses. Judging energy investment in statuary by the southern region alone, or the island as a whole (see Figure 7.1), statuary could be construed to adhere to cultural evolutionary explanations. These results, again, may stress the importance of attention to spatial variability in any attempt to develop a general chronology for the island.

Figure 7.1. Energy investment by century for Rapa Nui (northern and southern regions combined).

The theoretical insufficiency in the progressivist and typological approach of cultural evolutionary studies has been examined in detail before (Dunnell 1980, 1982). One of the empirical weaknesses of a cultural evolutionary approach arises in the difficulty in explaining temporal fluctuations in energy investment in the northern region of Rapa Nui. In addition, the southern region, and calculations for the island as a whole, show noticeable declines in energy investment in statuary in the 15th and 16th centuries. Cultural evolutionary explanations, making an inherent functionalist link between statuary and other social institutions, are unable to explain fluctuations or major declines in statuary without invoking the concept of cultural collapse. A decrease or decline in one aspect of social complexity implies a related decrease or decline in all others.

Many summaries have settled upon the notion of complete ecological and cultural collapse for Rapa Nui. Furthermore, these studies have even implied that a unsustainable practice of statue construction led to overexploitation of natural resources and was partly *responsible* for cultural and ecological collapse on the island (e.g., Bahn and Flenley 1992; Diamond 1995; Kirch 1984).

This is not to suggest that the cultural evolutionary framework is excessively simplistic, or that its proponents were unaware of the complexities of cultural variability. Sahlins, realizing the problems of associating monumental architecture directly with other social institutions, eventually offered instances where monumental architecture might be intensified at levels disproportionate to the rest of a society (1955, 1958). As Graves and Sweeney (1993:114) explain,

> Overelaborated ceremonial activities persisted as 'nonadaptive survivals' (Sahlins 1958:138) when a Polynesian group on an atoll or small island had diverged from a Polynesian society of a higher level in a more productive environment.

Additionally, Sahlins (1955) suggested that escalation in monumentality on Rapa Nui took place when energy that would have normally been channeled toward agricultural intensification (in an environment with more productive potential than that of Rapa Nui) was redirected toward statuary and other forms of monuments.

Scientific Evolution

Recent work on Rapa Nui has begun to question whether a prehistoric catastrophic collapse actually took place, and if so, whether the islanders themselves were directly responsible for such an event (Hunt and Lipo 2001; Rainbird 2002). The first written account of conditions on Rapa Nui in the early 1700's does not describe desperate or pathetic conditions that might be associated with utter catastrophic collapse. Dutch Admiral Roggeveen (Ruiz-Tagle 2004:37) reported the island environment to be:

> …outstandingly fruitful…this land, because of its rich earth and good climate, could be made into an earthly Paradise if it was properly cultivated and worked, which at present is done only to the extent that the inhabitants are required to for the maintenance of life.

Roggeveen (Ruiz-Tagle 2004:31) described the islanders as well:

> These people have well proportioned limbs, with large and strong muscles; they are big in stature…These people have also snow-white teeth, with which they are exceptionally well provided, even the old and hoary…

More generally, the empirical generalizations of cultural evolutionary efforts have been called into question by those working within a scientific evolutionary framework (e.g., Dunnell 1980; Graves and Ladefoged 1995; Graves and Sweeney 1993). Studies based on scientific evolution have attempted to identify specific impacts that large-scale investment of energy in monumental architecture or statuary may have imposed on prehistoric populations. A scientific evolutionary approach does not (or should not, at least) imply that energy investment in monumental constructions was necessarily beneficial or adaptive—only that in certain cases, the amount of energy invested was so extreme, that this investment must have impacted populations in one way or another.

The fact that scientific evolutionary studies in archaeology have focused on the potential benefits (rather than pitfalls) of energy investment in monumental constructions may be partly in reaction to cultural evolutionary accounts that sometimes implied that prehistoric populations squandered resources on monuments for lack of knowledge in resource management or their surrounding environment. However, empirically, the widespread and persistent or recurrent nature of energy investment in monumental construction also implies that the practice may have offered selective advantages rather than, or in addition to, disadvantages.

An Evolutionary Archaeological Framework

From a selectionist point of view, Dunnell (1989, 1999) and colleagues (Madsen et al. 1999) have explored the selective advantages offered by labor investment in monumental architecture in their “waste” or “bet-hedging” explanations (see Dunnell 1989:47). Dunnell (1999:245) suggests that engaging in the construction of monumental architecture (euphemistically termed "waste" as an activity unrelated to subsistence) has two primary effects:

> (1) it lowers population size directly through lower fecundity; and (2) it provides a sink of "excess" time and resources that can be devoted to subsistence/reproduction under stressful conditions.

Furthermore,

> …when environmental perturbations that adversely affect the carrying capacity for a particular set of people are on a large scale and unpredictable or have such a long period of recurrence as to render them so at the human scale, populations near carrying capacity would be catastrophically eliminated. Any populations with large amounts of waste would suddenly find themselves at a distinct advantage. They would have a smaller population and thus lower resource requirements as well as a reservoir of time to intensify subsistence (Dunnell 1999:245-246).

Subsequently, Madsen et al. (1999) have developed a mathematical model to demonstrate the long-term evolutionary success of a population that lowers population growth rates by channeling resources away from reproduction or subsistence and toward some form of "waste". The success of Madsen et al.'s model depends partly on their assumption that those individuals engaging in "wasteful" behavior somehow have better chances of surviving temporary environmental crises than those individuals that do not engage in "wasteful" behavior. This is a critical assumption that Madsen et al. make no attempt to justify. This point will be discussed below along with similar population models published by Boone and Kessler (1999) and Boone (2000).

The "waste" explanation for energy investment in monumental architecture offers temporal and spatial expectations for Rapa Nui that can be compared to the seriation and simulation results discussed in Chapter 6. Hunt and Lipo's (2001) survey of monumental architecture of Hawai‘i, and Aranyosi's (1999) analysis of monuments in Ireland both clearly state that the "waste" explanation predicts higher levels of energy investment in monumental architecture in less productive or more marginal areas of the respective island environments. And with reference to population dynamics, Dunnell and colleagues have suggested that energy investment in monumental architecture may be associated with a slowly growing population and one that is sustained below the mean carrying capacity. The only time that such demographic conditions exist in the computer simulation results for either region (or the island as a whole) is during the first half of the chronology. However, energy investment in statuary appears to show much greater levels in the second half of the chronology for the southern region and for the island as a whole. Furthermore, the "waste" explanation predicts the abandonment of wasteful behavior as populations experience severe and/or acute environmental pressures. Seriation and simulation results actually suggest an *increase* in energy investment in statuary as populations begin to experience more severe environmental pressures (a high population-to-carrying-capacity ratio).

Thus, empirically, the "waste" explanation may successfully account for an early peak in energy investment in the less productive northern region of the island. The subsequent overwhelming shift to energy investment in statuary in the southern region, on the other hand, does not appear to fit the expectations of the "waste" explanation. The late increase in energy investment in monumental statuary in the southern region of Rapa Nui appears to contradict expectations applied in previous studies citing the "waste" explanation.

Ultimately, the seriation and simulation results may offer only a partial test for expectations of the "waste" explanation. The simple relationship between population growth and energy investment in statuary generated through optimal path seriation and the computer simulation does not seem to fit the expectations of the "waste" explanation. However, population growth and energy investment in "waste" are not the only components of the "waste" explanation. Hunt and Lipo (2001) have interpreted the age-at-death statistics for different skeletal samples of Rapa Nui to fit demographic expectations outlined by Madsen et al. (1999). Although the computer simulation in this study has been designed to study age-at-death statistics in future analyses, the implementation in Chapter 6 does not allow an in-depth assessment of life-history variables for the simulated population. Future research and alterations to the computer simulation may help to derive a more explicit test for the "waste" explanation.

Dunnell's (1989) initial proposal of the "waste" explanation bridged a major theoretical gap by framing archaeological interpretation with Darwin's theory of natural selection. Subsequent research on the "waste" explanation by Madsen et al. (1999) has offered reasonable mathematical conditions, given certain assumptions, under which energy investment in cultural elaboration or "waste" might grow or be sustained solely through genetic selection. The assumptions upon which the evolutionary model is based are effectively the short-term causal mechanisms by which the "wasteful" phenotype experiences long-term success. The fact that these causal mechanisms remain as assumptions leaves room for further research and theoretical insight.

An Evolutionary Ecological Framework

Evolutionary ecologists have attempted to build upon the work of Dunnell and his colleagues to create a more comprehensive explanation for the persistence and variability of cultural elaboration (see Graves and Ladefoged 1995; Graves and Sweeney 1993). Primarily, evolutionary ecological work identifies potential short-term benefits associated with energy investment in cultural elaboration or monumental architecture to complement the long-term or genetic model outlined by the "waste" explanation.

Evolutionary ecological models tend to focus on competition and cooperation, and the role that labor investment in monumental architecture may play in relation to socio-ecological conditions. Citing work in Rotuma by Ladefoged (1993), Graves and Ladefoged (1995:164) propose that high levels of labor investment in monumental architecture signify a pooling of human and natural resources derived from political integration and that,

> …the pooling of labor and resources across territories as a consequence of political integration can confer selective advantages to individuals who will have access to resources during periodic climatic or environmental disturbances.

Graves and Ladefoged identify a key advantage that may accrue to certain individuals, and Ladefoged's work suggests that the integration that leads to advantages is often a result of intergroup aggression between territories with differential access to resources. However, there are also benefits of being part of a group that may render force or aggression unnecessary in group formation (Boone 1992).

Proposing monumental architecture or cultural elaboration as a byproduct of successful political integration, evolutionary ecological work presents an important method for empirical archaeological investigations within a well-defined theoretical framework. Other work within evolutionary ecology presents labor investment in monumental architecture as an active component, rather than a byproduct, in socio-ecological competition and cooperation. Neiman (1997) suggests that monumental architecture, as a form of "wasteful advertising" or conspicuous consumption (after Trigger 1990; Veblen 1899; Zipf 1949) may offer advantages to individuals. Amidst intergroup interaction, labor investment in monumental architecture may help to repel (or attract) potential competitors (or cooperators) through a symbol of the resources at one's disposal.

Recent theoretical work by Boone (1998, 2000) presents a critical link between the intergroup competition/cooperation model reviewed by Graves and Ladefoged (1995), the conspicuous consumption model outlined by Neiman (1997), and the "waste" explanation developed by Dunnell (1989, 1999) and others. Boone (2000:92) presents a mathematical model similar to the Madsen et al. (1999) population model to demonstrate that:

> …under fairly plausible conditions a strategy that requires the diversion of resources from the production of more offspring could be selected for if it sufficiently increased survivorship through recurrent bottlenecks.

Boone's work, however, is based on group formation and social inequalities. While Ladefoged's (1993) interpretation of pan-political integration in Rotuma is based primarily on spatial variability in access to critical resources, Boone (2000:97) hypothesizes through mathematical modeling that, "periods of increased interannual fluctuation in production should be associated with increased levels of population aggregation and intensification of production." Whether group formation takes place in response to spatial or temporal variability in resource availability, the resulting groups are assumed to be stratified socially. In Boone's model, stratification is the result of a primary landholder allowing other individuals or groups access to resources. Amidst temporal climatic fluctuations, Boone (2000:96) argues that, "With respect to food security alone, these additional territory sharers could be supported on this patch (albeit at a lower level of food security) at no extra cost to the primary holders."

The general idea is that primary landholders must, in most years, generate a surplus in order to establish a production routine that maintains a desired level of resource security for intermittent downswings in environmental productivity. Thus, in most years, the surplus yield can support additional occupants. Furthermore, additional occupants may offer additional labor to boost food production for the group to even higher levels.

The process of aggregation or group formation, in some cases, may be enough to establish a social hierarchy or priority in access to resources. Yet Boone returns to the idea of conspicuous consumption or "wasteful advertising" described by Neiman (1997) as a mechanism to enforce or strengthen social status differentiation, and Boone relates the concept directly to Zahavi's (1975, 1977) and Zahavi and Zahavi's (1997) biological notion of "costly signaling".

Boone (2000:92) reasons, as the "waste" explanation does, that as a result of individuals diverting resources away from subsistence to finance "costly signals", their fecundity is lowered, and through social status differentiation they establish priority in access to resources so that, "In times of shortage, lower-ranking families will be the first to be adversely affected; higher-ranking families would suffer last." Madsen et al. (1999) dismiss Boone's inclusion of costly signaling in population simulations as a mere proximate mechanism that the "waste" explanation does not require. What Madsen et al. do not acknowledge is that Boone has justified Madsen et al.'s assumption that there may exist some inherent link between reduced fecundity and enhanced survival through environmental crises. More precisely, energy investment in monumental architecture (or costly status signals) is the critical link. Boone's (2000:108) model ultimately predicts that:

> …the amount of cultural elaboration inherent in social-status reinforcement displays is some function of the average frequency and severity of demographic bottlenecks that have occurred in the past as well as the average total productivity…of the social group in which the lineage/individual is immersed.

This expectation, in turn, fits the seriation and simulation results described in Chapter 6 quite well. As the island population approaches some mean carrying capacity, the frequency and severity (relative to the population size) of demographic bottlenecks both increase (see Figure 7.2). For both the northern and southern regions of the island, those time periods for which the population is sustained at levels very close to the mean carrying capacity (and consequently experiences relatively frequent and severe bottlenecks) seem to relate to those periods of the chronology with increasing investment of energy in monumental statuary. Similarly, for those time periods in the simulation where the population is relatively small compared to the mean carrying capacity, bottlenecks are less frequent and less severe, and energy investment in monumental statuary appears to persist only at reduced levels.

Considering that Boone's work successfully integrates components of the "waste" explanation, the competition/cooperation models, and the costly-signaling approach, the accuracy with which it predicts empirical results from the seriation and simulation results of this analysis may be of little surprise. In reality, any explanation of the persistence and variability of prehistoric energy investment in monumental architecture is likely to be complex.

Future Directions - Cultural Autotomy?

Both evolutionary archaeological and evolutionary ecological frameworks have played a major role in developing a better understanding of why monumental architecture or statuary persisted at some times or in some areas of Polynesia and the Pacific but not

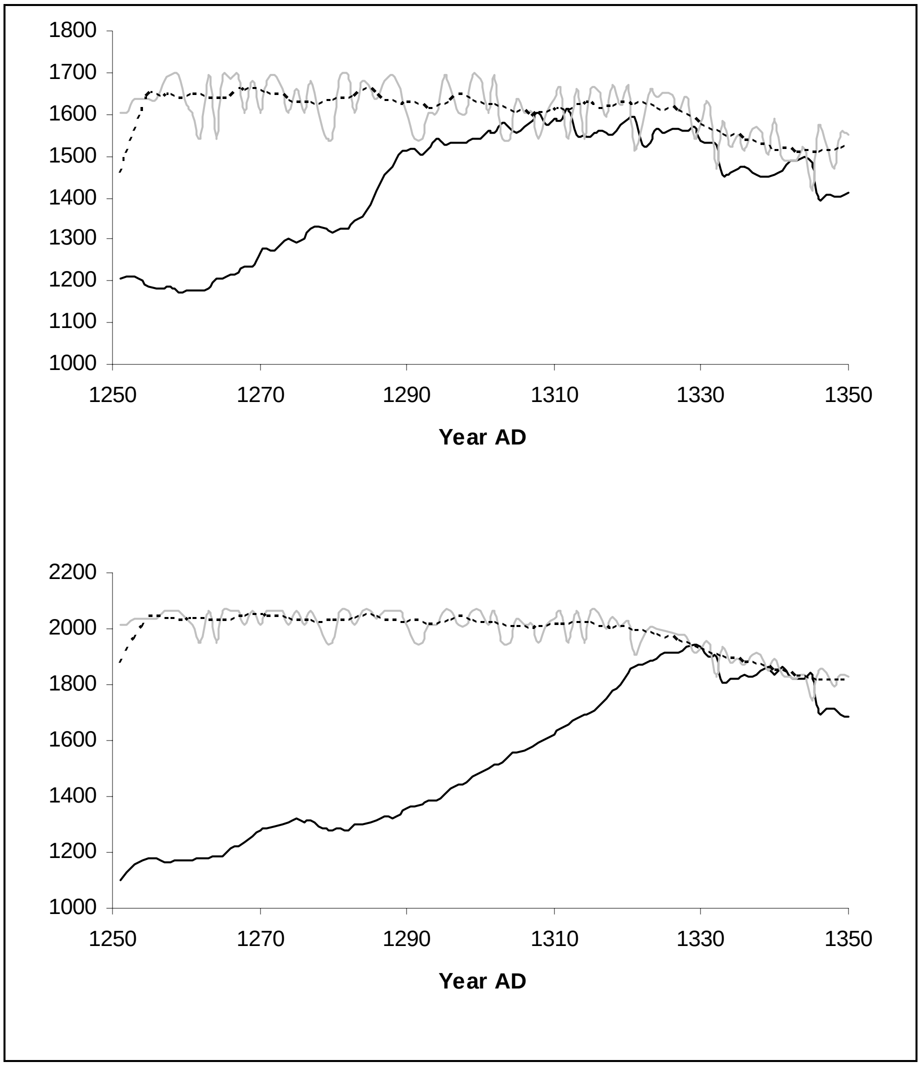


Figure 7.2. Carrying capacity (grey solid line) fluctuates randomly throughout the simulation. However as populations (black solid line) in the north (top) and south (bottom) approach a mean carrying capacity value (black dotted line), bottlenecks become increasingly frequent and severe.

others. However, the evolutionary models developed by Madsen et al. (1999) and Boone (1998, 2000) also raise questions, especially in terms of their social implications. Both models measure viability or success in terms of the overall population size. And while both models imply that energy investment in monumental elaborations may reduce fecundity, they also demonstrate how reduced fecundity can still lead to the most successful or sizeable populations in the long run (thus propagating the cultural practice of monumental construction). The individuals or lineages that finance these constructions at the expense of their own fecundity, at least according to Boone, are of an elite class.

In the long-term, both models suggest that these low-fecundity individuals (elites in Boone's model) will come to represent a major, or even overwhelming, percentage of the population. This result is, of course, contrary to the notion of "elite". Furthermore, a society for which the "elite" class constitutes 50-75% of the population (which could be the case after two to three centuries in Boone's simulation) may have little basis in reality. Thus, while evolutionary models have demonstrated a manner by which monumental construction and cultural elaboration may persist or proliferate, they do not always present evolutionary "strategies" by which corresponding social hierarchies may stabilize.

Boone (2000) recognizes that any social structure or status differentiation system that develops within a society (perhaps through costly signaling, for example) and that designates a particular subpopulation with lowest priority in access to resources may find itself with a selective advantage when faced with recurrent episodes of environmental stress or population bottlenecks. A demographic bottleneck implies that at least some percentage of the population will necessarily perish. However, if the subpopulation with lowest priority in access to resources is more susceptible to environmental perturbations than all others and constitutes a population that is large enough to absorb the brunt of the demographic bottleneck, then other high status (and maybe even some of the lower status) individuals will survive. Boone (2000) identifies this as an adaptive counter-collapse mechanism that may save populations from catastrophe or extinction.

Ultimately, Boone (2000:90) observes that, "the survivors of a population crash form the population base for the next period of growth," and it stands to reason that the more efficiently a subpopulation is sloughed, the more successful and resilient the surviving population may be. "Efficient" population sloughing depends on: (1) a population's ability to differentiate a social group that is large enough to absorb the stress or shock of environmental downswings; and (2) the ability to cast off the designated sloughing population rapidly so that individuals who will eventually perish do not exacerbate the bottleneck by consuming resources required for survival for higher-status individuals.

The implications of population sloughing, while ethically disturbing, are intriguing. If social complexity and status differentiation develop to fulfill the two conditions for "efficient" population sloughing, a complex demographic system develops that is not merely able to save a population from complete collapse or extinction (as Boone suggests) but rather able to persist *optimally* through recurrent bottlenecks. Whereas Boone's focus is the preservation of some core elite population, efficient sloughing may preserve the core, but at the same time minimize overall losses and more effectively retain the existing social structure.

The idea of population sloughing may seem antithetical to the concept of adaptive success. However, when success is measured by population size, sloughing may be an effective response to periodic demographic bottlenecks. Population size, as an indicator of adaptive success, depends both on maximization of gains (during favorable conditions) but also minimization of losses (during stressful conditions). There has been a tendency, in both biology and anthropology, to measure success by concentrating on how effectively an individual or population maximizes gains. However, a strategy may be suboptimal in maximizing gains but, given environmental variability, still dominate alternative strategies because it minimizes losses. It is also important to note that population sloughing is not purported to be a conscious social strategy of the elite or higher status individuals. The adaptive system requires only that social status differentiation leads to subpopulations with varying, strictly enforced priorities in access to resources. Costly signaling, in the form of monumental architecture or statuary, may be one archaeological representation of this type of strict social status differentiation.

As archaeological research continues to search for general or unifying theoretical principles to explain the prehistoric monumental architecture across the Pacific, population sloughing may prove to be an important area of research. In simple terms, population sloughing is the act of sacrificing part of the group to ensure the success of the remainder of the group. In this sense, population sloughing may have biological correlates, at the individual and group levels, for both human and non-human populations. Certain species of lizards, crabs, crickets, spiders, and other creatures have evolved the ability to spontaneously cast off or "autotomize" limbs (e.g., Amaya et al. 2001; Bateman and Fleming 2005; Fox and McCoy 2000; Pakarinen 1994; Wasson and

Lyon 2005). In many cases, autotomy may be a desperate measure to preserve the core of the individual—an extreme defense mechanism. At the group level, biological studies have demonstrated density-dependent changes in phenotypic representation (e.g., Clutton-Brock et al. 1997). These population biology studies may suggest that certain phenotypes are the first, and most rapid, to be sloughed under increased environmental pressures.

For non-human examples, financing (or coping with) costly *biological* signals (e.g., bright plumage, large antlers, large body size) places a serious burden on individuals. The elaborate and energetically-costly displays, while effective in attracting mates and repelling competitors during favorable environmental conditions, may also predispose individuals to failure under conditions of increased predation, increased parasitism, or critical resource shortages. Thus, costly biological signals may create an eminently "sloughable" biological class (e.g., males).

Humans also designate "sloughable" classes based on biological distinctions. Infanticide and geronticide, for example, are practiced cross-culturally to forcefully abandon either the young or the elderly. Financing costly *cultural* signals may also create a "sloughable" class, but one that is determined through social status differentiation rather than biology. By investing resources toward the construction of monumental architecture or statuary, individuals may create social distinctions in two ways. First, the monument may be accepted as a reflection of status—ensuring priority in access to resources for high-status individuals even under conditions of environmental stress. Second, a subpopulation is designated for a particular (monumental) form of craft specialization. Consequently, there is a subpopulation that may be divorced, to some extent, from direct procurement of (or access to) critical resources. Full-time, specialized occupations necessitate some form of redistribution of critical resources. Thus, financing costly cultural signals may not only distinguish separate social classes, but also enforce differential access to resources between classes.

Biological examples of autotomy should not dictate anthropological investigation on the topic, but may help to guide future research. There is a vast literature on the similarities and differences between biological and cultural evolution, and a direct application of biological theory or observations to anthropological research is not likely to offer a strong theoretical framework. However, in pushing evolutionary ecological and evolutionary archaeological work toward a general explanation of the persistence and variability of monumental architecture in prehistoric societies, biological studies may offer a useful analogy. Case studies of biological autotomy among lizards have already framed research questions in the context of social status (Fox et al. 1998).

Developing the Autotomy Model

Part of the challenge in presenting a novel evolutionary interpretation of cultural or biological phenomena is to determine how the model may be tested empirically, and whether data to test the model may already exist. The cultural autotomy model, introduced in this dissertation as a potential explanation for patterns stemming from analysis of prehistoric statuary on Rapa Nui and computer simulation, requires further attention to be more thoroughly developed and tested. Although explicit archaeological evidence of population sloughing on Rapa Nui has not yet been identified (or at least perceived as evidence of sloughing), the extreme geographic isolation of the island may have exacerbated environmental pressures. Mobility and migration are two important cultural responses to environmental pressure or crisis. However, when migration is not a desirable or efficient response (as would be the case for Rapa Nui), populations may be forced to bear the full force of environmental pressures without escape. At the same time, while the model stems from archaeological research on Rapa Nui, it is entirely possible that the island is not the ideal candidate to rigorously test the autotomy model.

There are however, initial expectations for the model that could potentially be tested on Rapa Nui with additional fieldwork, or even a methodical review of literature and excavation records. One of the expectations concerns burial practices or treatment of the deceased. Standardized practices for treatment of the dead on Rapa Nui are strongly suggested by archaeological and ethnohistorical evidence (e.g., Métraux 1940; Routledge 1919). Human remains were often disposed of through either cremation or burial. We might speculate, however, that in extreme events of population sloughing, the social status or sheer quantity of the deceased might lead to a treatment of remains other than traditional practices. Thus, widespread evidence of human skeletal remains that do not appear to be disposed of in a customary manner might potentially indicate a sloughing event or episode, if those remains are demonstrated to be contemporaneous. There has been considerable speculation on the island regarding cannibalism (e.g., Cervellino 1993; Heyerdahl 1958; Lee 1992). While archaeological evidence may not ultimately point to a prevalence of cannibalism, there are certainly examples of a peculiar treatment of the remains of the deceased. Smaller or less severe sloughing events may be more difficult to identify through the abundance or treatment of skeletal remains. And furthermore, archaeologists cannot simply surmise population sloughing or any other such phenomenon from a few skeletal remains. However, the possibility that population sloughing or autotomy may be reflected through temporally or spatially limited skeletal collections may encourage archaeologists to consider existing evidence from a new perspective.

Cultural autotomy and population sloughing might also produce a traceable effect in cultural transmission processes as well. Again perhaps more so in extreme cases, population sloughing may result in a significant loss of variability in artifact forms or styles. In the long term, or with repeated episodes of population sloughing, archaeologists could potentially detect a dampened innovation rate in artifact styles. Further research may be required to determine which artifacts would likely be affected through population sloughing. In Rapa Nui, cultural continuity is often visible through monumental or ceremonial remains, and the transmission of styles of these remains may be closely associated with high status individuals. Transmission patterns of artifact types that are more accessible or easily produced by lower status subpopulations might be more heavily influenced by population sloughing.

The treatment or disposal of the deceased and patterns of cultural transmission are just two preliminary avenues of testing for the cultural autotomy model. These tests may only be effective in cases where large subpopulations were lost in catastrophic or near-catastrophic sloughing events. However, one of the strengths of the autotomy model is that it does not depend on catastrophic conditions like previous accounts of Rapa Nui prehistory have. In fact, in a highly efficient form, population sloughing may amount to subtle periodic losses within a highly stratified population. Clearly, much work remains to determine the archaeological signature of minor sloughing events or sloughing routines.

There are case studies where population sloughing among human populations has been directly observed. Boone and Kessler (1999) cite case studies in the Caroline Islands (Sacks 1996), the Santa Cruz Islands (Firth 1959; Spillius 1957), the southwestern U.S. (Eggan 1966; Levy 1992), and Saharan Africa (Baier and Lovejoy 1977) in which social status differentiation led to what Levy (1992) refers to as a "sloughing off" of excess lower-status populations under adverse environmental conditions. These case studies may help not only to better understand the dynamics of population sloughing, but also to develop archaeological expectations.

Specifically, Tikopia in the Santa Cruz Islands appears to be an excellent candidate both for historical and archaeological studies of population sloughing. Natural disasters and the social practices in response to crisis have been documented in Tikopia on several occasions by anthropologists throughout the 20th century (Firth 1957, 1959, 1965; Kirch 1997; Kirch and Yen 1982; Spillius 1957).

Concluding Remarks

The seriation and simulation results within this study suggest that statuary or other costly cultural signals may be a density-dependent phenomenon. That is, energy investment in statuary is not related solely to population growth (as a cultural evolutionary framework might suggest), nor solely to some objective measure of environmental variability (as both evolutionary archaeologists and evolutionary ecologists have suggested). Rather, energy investment in monumental construction may be related to the way in which a population experiences or even interacts with the environmental carrying capacity. The ratio of population to carrying capacity, as measured in the agent-based simulation, may be one crude measure of the relationship between population and environment.

Within Polynesian studies, and within the discussion of explanations for prehistoric monumental architecture, archaeologists often attempt to classify environmental conditions through objective or quantitative terms. Dunnell (1989, 1999) and Madsen et al. (1999) attempt to identify quantitative patterns that define an "unpredictable" environment. Graves and Ladefoged (1995) and Graves and Sweeney (1993) attempt to distinguish between varying levels of "environmental" or "agricultural" productivity. In the Hawaiian Archipelago, this distinction within an island is often related to the windward/leeward geographic separation to distinguish between higher and lower levels of rainfall. For Rapa Nui, Hunt and Lipo (2001) use the coefficient of variation in rainfall over the last three decades to classify Rapa Nui in terms of unpredictability. Boone (2000), on the other hand, attempts to distinguish between environmental conditions by the "variance in productivity". What should be clear by this point is that there are many ways to interpret an environment to be variable or unpredictable by absolute measures. However, the work of Dunnell, Madsen et al., Boone, and others should also make it clear that even the most variable or unpredictable environments may have little impact on a small, slow-growing population. And conversely, relatively stable or predictable environments may inflict frequent

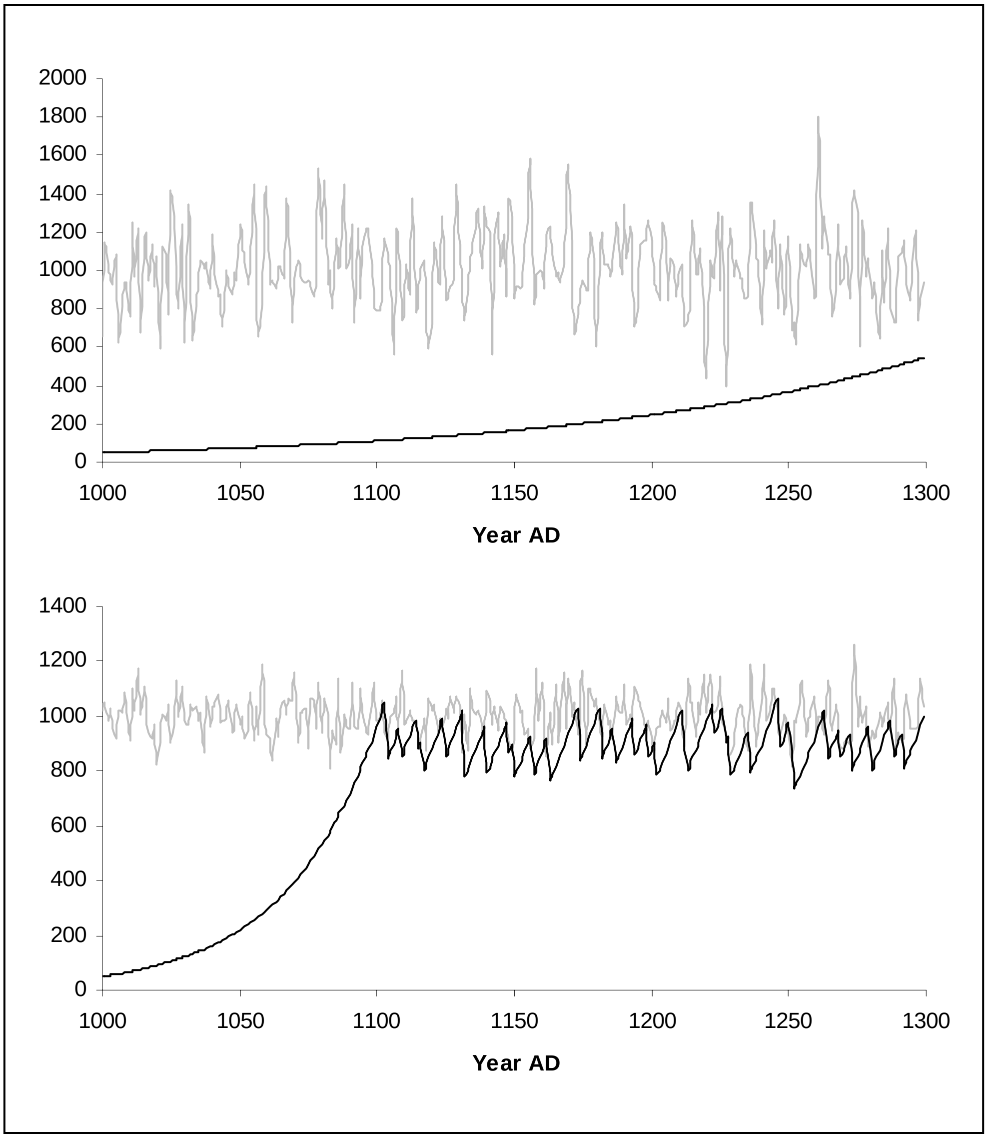


Figure 7.3. Extremely variable environmental carrying capacities (top, grey line) may have little or no effect on a slow-growing population (black line). However, even less variable environmental carrying capacities (bottom, grey line) may induce frequent and severe bottlenecks on a more rapidly growing population.

demographic bottlenecks upon a population (Figure 7.3). Thus, what may be of greatest importance is environmental variability *relative* to population size.

Therefore, the simulation approach described in this study and the attention to the population-to-carrying-capacity ratio (rather than objective measures of environmental variability) to explain prehistoric investment of energy in monumental statuary may help to guide future research on the monuments of Rapa Nui and elsewhere in the Pacific. Empirically, carrying capacities may be difficult to calculate. However, computer simulation, in conjunction with ethnoarchaeological studies and paleoenvironmental research may help to analyze complex dynamics between critical resources and offer estimates for carrying capacity. Boone's work, integrating concepts from both evolutionary archaeology and evolutionary ecology, proved to be exceptionally valuable to explain simulation and energy investment dynamics for this study of Rapa Nui. The notion of "cultural autotomy" is clearly an offshoot of the work of Boone and other archaeologists working within a scientific evolutionary framework. The seriation, simulation, and "cultural autotomy" analyses of Rapa Nui prehistory are, in many ways only exploratory research. However, it is precisely this type of research that helps us to evaluate existing models of explanation, communicate between one model and the next, and design future research for Rapa Nui and for general explanations of the persistence and variability of energy investment in prehistoric monuments throughout the Pacific.

APPENDIX A. THE OPTIMAL PATH SERIATION ALGORITHM

A fundamental assumption underlies all forms of seriation: artifacts proximate in origin are likely to be similar in style or form. The seriation method infers that artifacts similar in style or form are likely to be proximate in origin. This suggests that a good seriation will be one whose stylistic or formal evolution is gradual, the more gradual the better. The assumption here is that artifacts considered in a seriation share characteristics or features whose measures evolve gradually over time. Optimal path seriation searches for the ordering of artifacts that produces the most gradual evolution of all variables or features for all artifacts.

The term *artifact* may refer to objects, assemblages, components, deposits, etc. The terms *item*, *artifact* and *event* will be used interchangeably throughout the appendix. Measurable variables of artifacts are referred to as *features* (Rouse 1967). The production of an artifact is an *event* (Rouse 1939) and we are trying to determine the timing of that event. The term *sample* refers to a set of artifacts having similar form and function, and related provenience.

Style is defined as a set of common features of similar measure shared by separate artifacts of a sample. *Evolutionary* features have, for any item in a sample, measures that are similar to those of the items that preceded that item most recently in time (or distance). If a style is evolutionary, then at least some of the features that define that style must be evolutionary.

An "Evolutionary" Path

Seriation is based upon the assumption that the features analyzed evolve gradually and steadily, with artifacts more proximate in time, space, and/or cultural tradition tending to be more similar (Cowgill 1972; Dunnell 1970; Marquardt 1978); and upon the assumption that the underlying path is self-evident.

If we assume that each artisan in the manufacture of an artifact is influenced by similar artifacts that have been produced earlier, then there is an evolutionary process. This is not to say it is a Darwinian process. Often, stylistic features are considered to be selectively neutral (i.e., formal features whose variations carry no selective burden or advantage in relation to each other) and therefore not necessarily subject to processes of natural selection (Dunnell 1978; King and Jukes 1969; Leonard and Jones 1987; Neiman 1990; Teltser 1995). For our purposes, the notion of selective neutrality is not an issue (Bettinger et al. 1996). We need not insist that stylistic features be selectively neutral, just evolutionary as defined above.

The assumption that stylistic evolution of a feature is steady and gradual implies there is an underlying pattern, or function, that is smooth and continuous. Suppose we have a measure v of the formal features of our artifacts. We consider the value v_{fi} of feature f of item i, to be a function of time, t, $v_{fi} = v_f(t_i)$. If we know the date t_i for each item i, for each feature of our sample we might infer (for example, using regression) a path that reflects the underlying function (see Figure 1 where artifacts are represented by solid circles). Unfortunately, we do not know the values t_i.

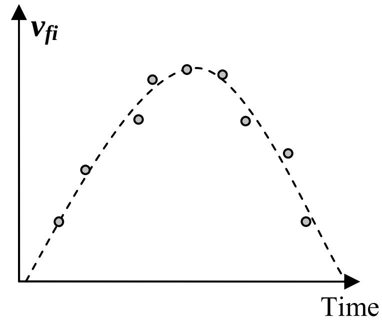


Figure A.1. Formal variation.

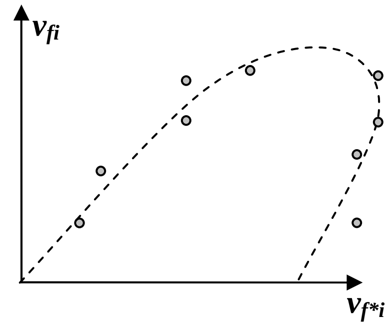


Figure A.2. Formal variation.

As we move along the path we are moving continuously through time. Consider the graph of feature *f* plotted against feature *f** in Figure 2. Time is implicit in the path. Unfortunately, using only two dimensions, or features, there is usually so much variation or deviation ("noise") from any ideal path that it is often difficult to discern a best path with confidence. It becomes more difficult, using regression analysis, to find a good, not to mention a best path in higher dimensions. There is the added problem in occurrence seriation that investigators have restricted themselves to just two possible values of v_{fi}, making it difficult to determine a meaningful path.

The myriad of seriation techniques is devoted to solving this problem. They all assume that such a unidirectional path exists and that its trajectory is self-evident from the artifacts themselves. Optimal path seriation makes the same assumptions.

Deriving Optimal Path Seriation

We model the manufacture of artifacts as a discrete process in space and time, and a manifestation of a particular culture (or cultural or local tradition). For each feature *f* and each item *i* we define the *value function*, $v_{fi} = v_f\,(c_i, x_i, y_i, z_i, t_i)$, that represents the measure for that feature and item, where x_i, y_i and z_i are the normal spatial dimensions representing the physical location of item i, and c_i and t_i represent respectively the culture that produced the artifact and the date of manufacture.

In seriation, v_{fi}, x_i, y_i and z_i are data while c_i and t_i are decision variables. The values, v_{fi}, of the various features of individual artifacts are known, and assumed to be the result of the particular time and culture of their manufacture. If the function v_{fi} can be represented mathematically, and if it is invertible, then the date is implicitly a function of the culture, value and location. Even if the function v_{fi} is not invertible it may be possible to tease out a "best fit" for assigning dates and cultures to artifacts.

To begin with, formal differences among artifacts are assumed to be a result of stylistic evolution reflecting time. Optimal path seriation is later extended to account for multiple cultural traditions and/or spatial variation. Three postulates provide the foundation to develop a theory of seriation:

1. *Change* – we expect each item to be a combination of innovation and the influence of the items that preceded it, not necessarily just its immediate predecessor, resulting in measurable change from one item to the next;
2. *Magnitude* – we expect the absolute value of the rate of change for an individual feature to be small; and
3. *Direction* – we expect the direction of change for an individual feature could itself occasionally change (from increasing to decreasing or *vice versa*).

Not all features are necessarily consistent with these postulates. A practitioner must judge to what extent his/her artifacts and features conform. If the fit is poor, an alternative to optimal path seriation should be considered.

The first postulate, change, stipulates that the style of any individual artifact may be influenced by any number of preceding artifacts. This means that instead of dealing with the difference between two successive items, we prefer to relate each item to a collection, if not all, of the items that preceded it. There is no limit to the number of ways this can be done. To relate an event to all previous events in an ordered sample, we may define the *smoothed average* of the first i items as

$$v'_{fi} = \alpha v_{fi} + (1-\alpha) v'_{fi^-} \qquad f \in F,\ i \in I,\ i \neq i_1,\ 0 \leq \alpha \leq 1 \qquad \text{(Equation A.1)}$$

where F is the set of features for which our practitioner believes artifacts similar in style or form are likely to be proximate in origin, I is the set of items in the sample, i_1 is the first item in our chronological ordering, and i^- represents the item that immediately precedes item i. We define $v'_{fi} = v_{fi}$ for $i = i_1$. Then v'_{fi} is a weighted average of the values for feature f of item i and the items that precede item i. This smoothing has the advantage of weighting the most recent events most heavily, but “remembering” even the most distant past events. Users can choose how heavily to weight recent events by adjusting the value of the smoothing constant α.

Our model will find a best path by considering all possible paths, or orderings of events, and choosing the one that minimizes the distances between successive events. Instead of looking at the distance of one event from its preceding event, we will look at the distance of the event from the smoothed average for its preceding event – the point on the smoothed path that corresponds to the preceding event.

The second postulate, magnitude, states that the absolute value of the rate of change for an individual feature should be small. We define the *difference*, d_{ii^-}, as the Euclidean distance between successive events, i^- and i,

$$d_{ii^-} = \sqrt{\sum_{f \in F} \left(v_{fi} - v'_{fi^-} \right)^2} \qquad i \in I \qquad \text{(Equation A.2)}$$

Alternatively we could use the Manhattan distance between successive items:

$$d_{ii^-} = \sum_{f \in F} \left| v_{fi} - v'_{fi^-} \right| \qquad i \in I \qquad \text{(Equation A.3)}$$

or Hamming distance:

$$d_{ii^-} = \sum_{f \in F} \delta_{fii^-} \qquad i \in I \qquad \text{(Equation A.4)}$$

where δ is the difference function, defined as:

$$\begin{aligned} \delta_{fii} &= 0 \qquad if \;\; v_{fi} = v'_{fi^-} \\ \delta_{fii^-} &= 1 \qquad if \;\; v_{fi} \neq v'_{fi^-} \qquad f \in F;\; i \in I \end{aligned} \qquad \text{(Equation A.5)}$$

Consistently large variations in one feature should not overwhelm consistently small variations in another, so in practice we must normalize each feature's contribution to the distance. Distances are measured in standard deviations in all dimensions. The *rate of change*, r_{ii^-}, between successive items is given by:

$$r_{ii^-} = \frac{d_{ii^-}}{t_i - t_{i^-}} \qquad i \in I \qquad \text{(Equation A.6)}$$

The third postulate, direction, means we are concerned with the magnitude of the rate of change rather than its direction, or even its change of direction. The use of Euclidean distance ensures this, as it works with the squared value of the change of each feature from one item to the next. Similarly, Manhattan distance works with the absolute value and Hamming distance only uses values of zero and one.

We can now build a model based upon our three postulates. We define our *objective function*,

$$g(t) = \sum_{i \in P'} r_{ii^-}^2 \left(t_i - t_{i^-}\right) \qquad \text{(Equation A.7)}$$

where $t = (t_1, t_2, \ldots, t_n)$ for the n items of our sample, $P = P(I)$ is the permutation or ordering of the items in our sample I determined by the values of t, and P' is P minus its first item i_1. Our objective, rather than minimizing the total distance of the seriation, is to choose an ordering and assign dates to our artifacts so as to minimize $g(t)$, the weighted sum of the squares of the rates of change, where the weights are the durations of the rates of change. The rates of change will be minimized by spreading the events out over as long an interval as possible. Therefore, if a range of dates is not known, we will arbitrarily assign an earliest and latest possible date for our events (implying that t_1 and t_n are fixed and therefore not decision variables).

Our objective function is a measure of how well our seriation fits our assumptions for stylistic evolution. First, it incorporates in measuring change, the influence of all earlier items, not just the last. Second, it minimizes the magnitude of the rate of change. Third, using the square of the rate of change allows reversals in the direction of changes regardless of how we compute d_{ij}; and penalizes large changes disproportionately, further minimizing large rates of change. Fourth, it weights each rate of change by its duration, minimizing overall change, or rate of change, creating the most gradual possible path.

Rewriting $g(t)$,

$$g(t) = \sum_{i \in P'} \frac{d_{ii^-}^2}{t_i - t_{i^-}} \qquad \text{(Equation A.8)}$$

and applying the necessary conditions for a minimum solution, namely that the partial derivatives must all be zero, we get:

$$r_{ii^+} = r_{ii^-} \qquad i \in P',\ i \neq i_n \qquad \text{(Equation A.9)}$$

where i^+ represents the event that immediately follows event i. This implies, in the best possible situation, the rate of change is the same from one event to the next. Let us call that rate of change r_P. We know that for any permutation P, we must have:

$$\frac{d_{ii^-}}{t_i - t_{i^-}} = r_P \qquad i \in P' \qquad \text{(Equation A.10)}$$

Therefore,

$$r_P \sum_{i \in P'} \left(t_i - t_{i^-}\right) = \sum_{i \in P'} d_{ii^-} \qquad \text{(Equation A.11)}$$

which in turn implies:

$$r_P = \frac{\sum_{i \in P'} d_{ii^-}}{t_{i_n} - t_{i_1}} \qquad \text{(Equation A.12)}$$

The rate of change, which is constant from one event to the next, must be equal to the total change divided by the total duration. The total change depends upon the ordering of the events, so the value of r_P depends upon the permutation P.

The fact that the rate of change is constant from one event to the next allows us to rewrite our objective function. From Equations A.8 and A.10:

$$g(t) = r_P \sum_{i \in P'} d_{ii^-} \qquad \text{(Equation A.13)}$$

and from Equations A.12 and A.13:

$$g(t) = \frac{\left(\sum_{i \in P'} d_{ii^-}\right)^2}{t_{i_n} - t_{i_1}} \qquad \text{(Equation A.14)}$$

Since the dates, t_i, are known for $i = i_1, i_n$, and since the distance d_{ij} is always nonnegative, minimizing $g(t)$ is equivalent to the constrained optimization problem:

$$\begin{array}{lll} \underset{\text{over } t}{\text{Minimize}} & \sum_{i \in P'} d_{ii^-} & \\ \text{subject to} & r_{ii^+} = r_{ii^-} & i \in P',\ i \neq i_n \\ & t_i > t_{i^-} & i \in P' \end{array} \qquad \text{(Equation A.15)}$$

We have shown that minimizing the weighted sum of the squared rates of change, Equation A.7, is equivalent to minimizing the sum of the changes themselves, provided the rate of change remains constant from one event to the next. Given an ordering of events, it is straightforward to satisfy the rates of change constraints by computing optimal dates for the events. From Equation A.10:

$$t_i = t_{i^-} + \frac{d_{ii^-}}{r_P} \qquad i \in P' \qquad \text{(Equation A.16)}$$

Since Equation A.16 is readily satisfied given any ordering, our problem comes down to finding a permutation that minimizes the sum of the distances between events along the optimal path to find a best seriation. We can assign dates for individual events by solving Equation A.16.

Rather than Equation A.7 we could have chosen as our objective function the weighted sum of the rates themselves (not their squares):

$$g'(t) = \sum_{i \in P'} r_{ii^-}\left(t_i - t_{i^-}\right) \qquad \text{(Equation A.17)}$$

which simplifies immediately to:

$$g'(t) = \sum_{i \in P'} d_{ii^-} \qquad \text{(Equation A.18)}$$

which appears to be where we ended up anyway (Equation A.15). The difference is that Equation A.15 also includes the rate constraints (Equation A.9) which enable us to assign dates to items. The objective function expressed in Equation A.18 does not depend upon the dates t_i and does not give us a way of assigning dates to artifacts. This is of particular concern where a practitioner may have estimates of dates for at least some of the artifacts being seriated and where the rates of change cannot be kept constant. The *OptiPath* software includes an algorithm for optimizing a seriation for artifacts with time estimates:

$$\begin{array}{lll} \underset{\text{over } t}{\text{Minimize}} & \sum_{i \in P'} r_{ii^-}^2 \left(t_i - t_{i^-}\right) & \\ \text{subject to} & t_i > t_{i^-} & i \in P' \\ & t_i > E_i & i \in P' \\ & t_i < L_i & i \in P' \end{array} \qquad \text{(Equation A.19)}$$

where E_i is the earliest allowed date for item i and L_i is the latest. The objective function of Equation A.18 is not suitable for this problem but that of Equation A.7 is.

Occurrence Seriation

Suppose $v_{fi} = 0$ or 1 for all $f \in F$, $i \in I$, and the durations of the intervals separating events are ignored. Equivalently, we can assume the intervals are constant:

$$t_i - t_{i^-} = k \qquad i \in I,\ i \neq i_1 \qquad \text{(Equation A.20)}$$

where k is a constant. Without loss of generality, we can assume $k = 1$. Assuming $v_{fi} = 1$ indicates the presence of a feature, and $v_{fi} = 0$ indicates the absence, we add two fictitious items i_0 and i_{n+1}, to our sample I and we force i_0 to be first in any ordering and i_{n+1} to be last. Let $v_{fi} = 0$ for $i = i_0$ and $i = i_{n+1}$ for all features $f \in F$. We will compare each item only to its predecessor ($\alpha = 1$) and we will not normalize the data. We define the delta, or difference, function, δ, as we did in Equation A.5. From Equation A.4 we have

$$d_{ij} = \sqrt{\sum_{f \in F} \delta_{fij}^2} \qquad i, j \in I \qquad \text{(Equation A.21)}$$

From Equation A.7 for our objective function, $g(t)$, and since $\delta_{ij}^2 = \delta_{ij}$ and $t_i - t_{i-} = 1$,

$$g(t) = \sum_{i \in P} \sum_{f \in F} \delta_{fii^-} \qquad \text{(Equation A.22)}$$

If a perfect seriation exists, the value of $g(t)$ will be $2m$, where m is the number of features in F. Any other seriation will have a larger objective function value. Therefore, the occurrence seriation problem is a relaxation of OPS where the constraints requiring the rate of change to be constant have been relaxed (ignored) and the distance between events is the sum of the feature differences δ_{ij} (Hamming distance).

Occurrence seriation ignores valuable information by translating continuous values to discrete classifications, often resulting in subgroups with indistinguishable members. Occurrence seriation falls short of OPS on two other accounts: occurrence seriation orders events without dating them, and occurrence seriation offers no objective means of finding the best possible seriation when a perfect seriation is not possible.

Frequency Seriation

Frequency seriation is a means of treating assemblages of artifacts as a single unit sharing a common date. Instead of measuring a single feature of an individual artifact, frequency seriation looks at the fraction of artifacts in the collection which share a common trait (style or feature value).

If we treat each assemblage as an artifact, and each trait as a feature, then frequency seriation is a special case of OPS. The disadvantage of frequency seriation is that it depends upon unimodality for each trait, because of the heuristic techniques proposed for performing the seriation. However, it is difficult to argue unimodality from first principles. The manufacture of artifacts is a discrete process by individuals whose idiosyncrasies will be reflected in variations that may violate continuity, smoothness, monotonicity and even unimodality.

Cultural Traditions

We now expand our model to accommodate geographic locality and cultural traditions; although this aspect of OPS is not applied to Rapa Nui statuary. An evolutionary path may, in some cases, reflect geographical dispersal as well as temporal evolution. One way to overcome this is to restrict samples geographically, assuming local stylistic traditions.

A similar problem is that there may be more than one contemporaneous stylistic or cultural tradition, even within a single geographical locale. Again it would be possible to overcome this if we were able to separate items according to cultural tradition.

We refer to both cases as *cultural traditions*, even though the same cultural tradition may exist in different locales, each exhibiting its own stylistic evolution for the items under consideration. In both cases we are effectively dividing a sample into multiple samples. If we define $P_c = P_c(I)$ to be a permutation of the items assigned to cultural tradition c, we have from Equation A.8:

$$g(c,t) = \sum_{c} \sum_{i \in P_c^{'}} \frac{d_{ii^-}^2}{t_i - t_{i^-}} \qquad \text{(Equation A.23)}$$

where P_c' is the set $P_c(I)$ minus the element i_1, the first item in the chronological ordering of $p_c(I)$. From Equation A.15 the optimal path problem becomes:

$$\begin{array}{llll} \underset{\text{over } c,t}{\text{Minimize}} & \sum_{c} \sum_{i \in P_c'} d_{ii^-} & & \\ \text{subject to} & r_{ii^+} = r_{ii^-} & i \in P_c' & \text{(Equation A.24)} \end{array}$$

Steady, gradual evolution of style is more likely than many sudden large changes in style. Such large sudden changes are better accommodated by assigning a new culture c, or, in effect, a new style.

Solving the Optimal Path Seriation Problem

Our solution technique is a two step procedure. First, we choose a possible assignment of items to cultures, c. Second, we treat each cultural tradition as a separate problem in seriation. Once we have found the best possible seriation for each cultural tradition subproblem, we then choose a new assignment of cultural traditions and repeat the process until we have found the best overall answer.

We have shown that the constraints (that the rates of change must be the same for all items) are easily satisfied given any ordering. So we begin by ignoring the constraints and worry about finding an optimal ordering of the items:

$$\underset{\text{over } t}{\text{Minimize}} \quad \sum_{i \in P_c'} d_{ii^-} \qquad \text{(Equation A.25)}$$

As formulated, the distances $d_{ii'}$ depend upon the ordering $p(I)$, because we used the smoothed average of observations, Equation A.1, in determining the rate of change of features. No well-known specialized algorithms for solving this problem exist. If the smoothed average is not used ($\alpha = 1$), the problem is a variant of the well known traveling salesman problem, namely the shortest Hamiltonian path problem. The traveling salesman problem is notoriously difficult. The field of operations research includes a rich literature on solving traveling salesman problems (Nemhauser and Wolsey 1999, Rayward-Smith et al. 1996). Specific algorithms are beyond the scope of this appendix. None is guaranteed to deliver a best answer within a reasonable amount of time. However, many do achieve very good answers relatively quickly. For large problems (more than twenty artifacts) a good computerized algorithm will almost always perform far better, and faster, than a human can.

Optimal path seriation uses a rather simple simulated annealing heuristic technique (Rayward-Smith et al. 1996:27) to solve the traveling salesman problem, resulting in what may be less than optimal answers, but nearly optimal given restraints in time and computing power. The *OptiPath* software implementing the algorithm is freely available for non-commercial purposes at http://www.shepardsons.net/optipath.html.

APPENDIX B. *RAPASIM* COMPUTER SIMULATION

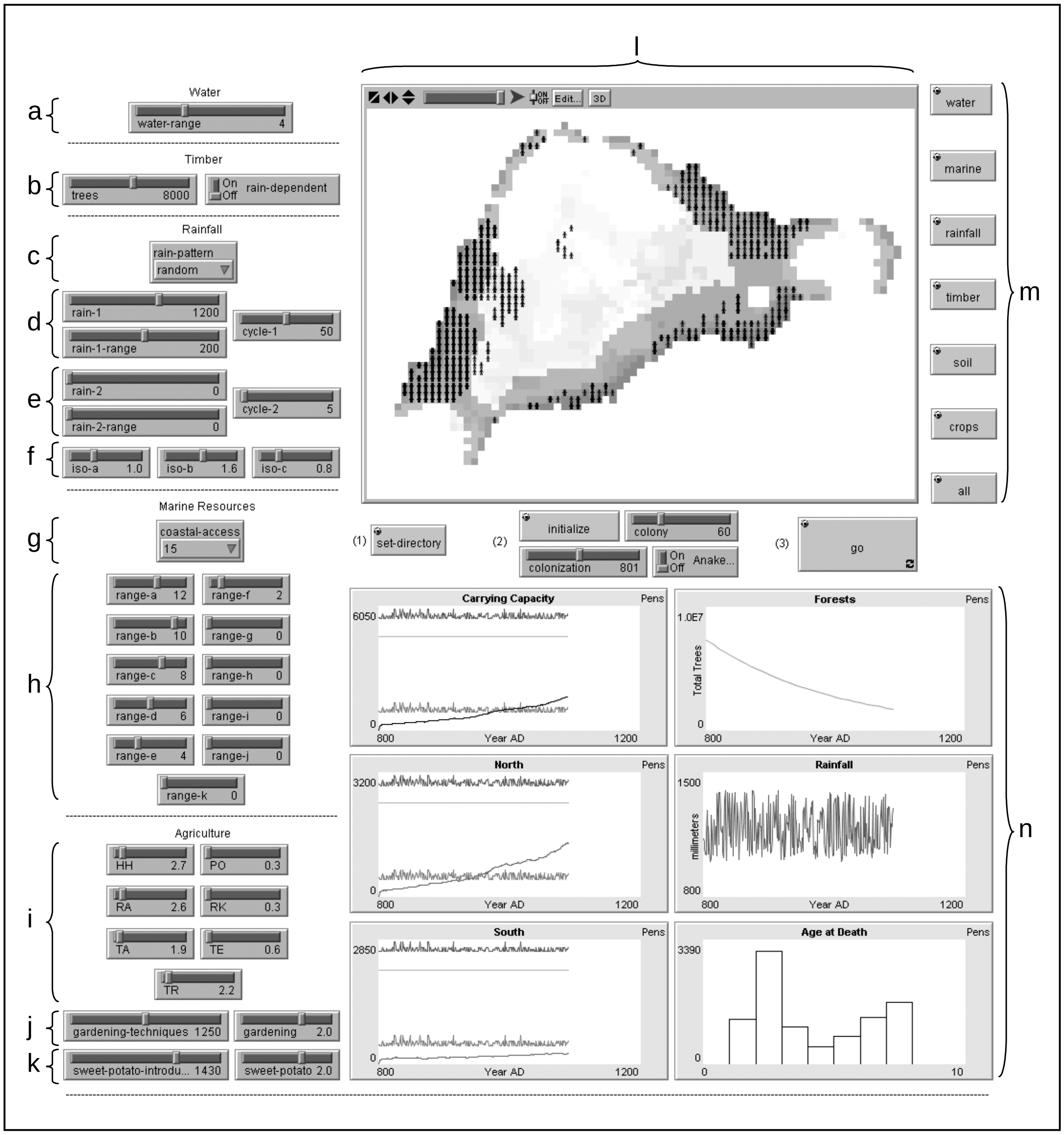


Figure B.1. *RapaSim* user interface.

Setup Controls

(1) The *set-directory* button allows the user to identify the *RN* folder containing geographic reference files on his or her computer. This must be done once before running the simulation in order to import GIS data.

(2) The *initialize* button will access geographic reference files from the *RN* folder to assign initial conditions to all environmental variables for all cells. The number of agents designated by the *colony* slider will then be created. The starting locations of these agents on the landscape is based on the *Anakena* switch. By toggling the *Anakena* switch to ON, the user indicates that all agents will be placed in one cell on the *Anakena* beach. By toggling the *Anakena* switch to OFF, the agents will be placed randomly on cells around the island landscape that offer at least 1 marine resource. Simulation of environmental processes begins at AD 700, but users may adjust the *colonization* slider to determine at what point the islanders will first appear in the simulation.

(3) The *go* button begins the simulation.

Water

(a) The *water* slider determines the maximum cost-distance (in level kilometers) from sources of potable water at which islanders may inhabit cells.

Timber

(b) The *trees* slider controls the maximum number of trees within each cell in the simulation space. Each cell will initially host a random number lesser than or equal to the value of the slider. The *rain-dependent* switch allows the user to determine whether initial forest conditions are dependent on rainfall isohyets or not. Setting the *rain-dependent* switch to ON multiplies the random value of trees in each cell by the corresponding isohyet value for that cell.

Rainfall

(c) The *rain-pattern* chooser tool allows for the user to determine whether rainfall will be random or based on two alternating cycles.

(d) If the user chooses RANDOM from the *rain-pattern* tool, the base amount of rain (in millimeters) for each year in the simulation will be a random value between *rain-1* minus *rain-1-gauge* and *rain-1* plus *rain-1-gauge*.

(e) If the user chooses CYCLICAL from the *rain-pattern* tool, then for the first *cycle-1* years of the simulation the amount of rainfall for each year in the simulation will be a random value between *rain-1* minus *rain-1-gauge* and *rain-1* plus *rain-1-gauge*. For the next *cycle-2* years of the simulation the amount of rainfall for each year in the simulation will be a random value between *rain-2* minus *rain-2-gauge* and *rain-2* plus *rain-2-gauge*. These alternating cycles continue indefinitely for the simulation.

(f) The *iso-a*, *iso-b*, and *iso-c* sliders act as multipliers to simulate the varying benefits or effects of increased rainfall at higher elevations. Base rain values are multiplied by *iso-a* for all cells in the simulation between sea-level and 100m elevation. Base rain values are multiplied by *iso-b* for all cells in the simulation between 100m and 200m elevation. Base rain values are multiplied by *iso-c* for all cells in the simulation above 200m elevation.

Marine Resources

(g) The *coastal-access* chooser tool allows for the user to determine the slope (in degrees) of terrain on shoreline cells that prohibit immediate access to marine resources. Any shoreline cell characterized by terrain with a slope greater than the value of the *coastal-access* chooser will only benefit from marine resources as a result of proximity to another shoreline cell that does have immediate access to marine resources. Any shoreline cell characterized by terrain with a slope less than the value of the *coastal-access* chooser will benefit maximally from marine resources. Hereafter, these cells will be referred to as coastal-access shoreline cells.

(h) Sliders *range-a*, *range-b*, *range-c*, … , *range-k* determine the amount of marine resources (in number of islanders sustainable) available in cells at progressively increasing distances from shoreline cells with immediate access to marine resources. Each range refers to cells at a particular cost-distance from coastal-access shoreline. Cells pertaining to *range-a* reside at less than 1 km on flat terrain, (or a shorter distance on steeper terrain requiring equivalent energy to traverse) from coastal-access shoreline cells. Cells pertaining to *range-b* reside between 1 and 2 km from coastal-access shoreline cells. Cells pertaining to *range-c* reside between 2 and 3 km from coastal-access shoreline cells. All cells on the island are categorized likewise up to those pertaining to *range-k* at the greatest distances from coastal-access shoreline cells. A *range* slider value of zero indicates that the cell cannot sustain any islanders by marine resources alone.

Agricultural Resources

(i) These sliders determine the amount of agricultural resources (in number of islanders sustainable) available in cells based on the geographically differentiated volcanic flows of the island (González-Ferrán et al. 2004). This value is multiplied by a rainfall factor and a slope factor in each cell to determine the actual number of resources (or islanders) that the cell will produce (or support). *HH* refers to the Hiva Hiva and Anakena flows; *PO* refers to the Poike flow; *RA* refers to the Rano Aroi flow; *RK* refers to the Rano Kau flow; *RR* refers to the Rano Raraku flow; *TA* refers to the Tangaroa flow; and *TR* refers to the trachyte-rhyolite flows.

(j) The *gardening-techniques* slider determines the date in the simulation at which advances in gardening technology first begin to benefit agricultural production. The *gardening* slider determines the factor by which all volcanic substrate slider values are multiplied as a benefit of changes in agricultural technology in years subsequent to the *gardening-techniques* slider.

(k) The *sweet-potato-introduction* slider determines the date in the simulation at which the sweet potato was introduced as a critical staple crop. The *sweet-potato* slider determines the factor by which all volcanic substrate slider values are multiplied as a benefit of sweet potato production in years subsequent to the *sweet-potato-introduction* slider.

Output

(l) The viewer offers a visual representation of the resources and agents in the simulation. This viewer image depicts agent dispersal on a landscape where darker cells indicate higher total (marine plus agricultural) resources. The user can freeze the viewer (for faster processing) by toggling the switch on the viewer to OFF.

(m) At any point during the simulation, the user can use these buttons to display the color-coded spatial distribution of different resources in the viewer. The *soils* button will display the productivity of soils based on volcanic substrate whereas the *crops* button will display overall agricultural yield. The *all* button will display the total resources for each cell (marine plus agricultural resources).

(n) The interface plots several different graphs as the simulation runs. *Carrying Capacity* plots several different variables against time. These variables include the island's total resources (or number of islanders that can be sustained), the island's marine resources, the island's agricultural resources, and the island's total population of agents. *North* plots the total number of marine resources, total number of agricultural resources, total number of resources in the northern region of the island, and total agent population in the northern region against time. *South* plots the total number of marine resources, total number of agricultural resources, total number of resources in the northern region of the island, and total agent population in the southern region against time. *Forests* plots the total number of trees on the island against time. *Rainfall* plots the base amount of rain in millimeters for each year of the simulation. *Age at Death* plots a histogram for those agents that have died in the simulation. At the time each agent dies (and is removed from the simulation), his or her age is recorded. The histogram is divided into the following age ranges: 0-2; 3-12; 13-18; 19-24; 25-29; 30-40; and 40+.

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