Human settlement of Easter Island – a competing hypothesis

Anthony Cole[1] and John Flenley[2]

[1] Pansophy Limited, Private Bag 1409 and Landcare Research Ltd, Private Bag 11052, Palmerston North, New Zealand.

[2] School of People, Environment and Planning, Private Bag 11222, Massey University, Palmerston North, New Zealand.

ABSTRACT: This paper draws on epistemology, theory, published data, hypothesis testing and synthesis to explore the predictive and explanatory power of a far-from-equilibrium interpretation of the history of human settlement on Rapa Nui. Our interpretation of the last 1500 years of human settlement on Rapa Nui provides an important competing hypothesis by which to test the explanatory power of earlier equilibrium interpretations of this history. Our evaluation of this competing hypothesis suggests that it provides, overall, a more satisfactory theory that has interesting implications for the goal of sustaining human civilisation.

KEY WORDS: complex system, equilibrium, far-from-equilibrium, human civilisation, population collapse, sustainability.

This paper seeks to explore the power of far-from-equilibrium theory to explain the progress of human civilisation on Rapa Nui. It progresses deductively from background theory to a series of propositions that seeks to refute using published field data. The key assumptions of this experimental approach are acknowledged.

Pristine island ecosystems are laboratories for studying the interaction of human social development with the environment (Flenley & Bahn 2003). Unfortunately, the variables responsible for these historic natural experiments were never monitored. For this reason it is difficult to derive a clear understanding of what happened and why (Chesson & Case 1986). The present authors seek to overcome this problem with the aid of archaeological and palaeoecological data. The task of reconstructing past environmental changes in association with theory testing helps overcome the human tendency to interpret historic events from the reference point of current knowledge (Quinn & Dunham 1983). Understanding this tendency, it comes as no surprise that past attempts to interpret civilisation rise and decline on Rapa Nui principally involve equilibrium theories of environmental, social and economic organisation and development (Brander & Taylor 1998; Erickson & Gowdy 2000; Mahon 1998; Rafael & Decker 2000).

Models assuming the existence of equilibrium conditions are not the endpoint for testing theory, but rather the beginning. This is especially because it is difficult to test the explanatory power of theory in isolation from a competing hypothesis (Platt 1964). This point is noted only to emphasise another perennially made, but often ignored one, that science progresses by mustering evidence to disprove hypotheses, not by finding evidence to support them (Popper 1963; Loehle 1983). Modelling research related to the history of Rapa Nui would benefit from: (i) competing hypotheses against which to assess the explanatory power of theory, and (ii) a hypothesis testing framework designed with a refutation goal-orientation in mind. This paper seeks to address both of these needs.

The remainder of this paper is organised in a way that provides: (a) an evaluation of relevant theory; (b) articulation of working hypotheses, assumptions and refutation criteria; (c) a stepwise account of experimental method; (d) a progressive, point-by-point evaluation of field data; (e) discussion of results and development of a summary table; and (f) conclusions.

1. Theoretical context

The history of human settlement on Rapa Nui may be viewed through the general equilibrium theory of conventional economics (Jackson *et al*. 1994, 1997) or the non-equilibrium (DeAngelis & Waterhouse 1987) and far-from-equilibrium (Gunderson & Holling 2002) theories of ecology.

The fact that ecology and conventional economics work from fundamentally different paradigms begs an answer to a question that has been largely ignored. Do economic systems behave differently from ecological systems? Given that both ecological and economic systems are subject to the same natural laws (i.e. entropy, and the conservation of mass and energy, etc.); both systems should be organised by forces of a similar character that manifest similar behaviour. Why is it then that conventional economics (Byrns & Stone 1992; Edward-Jones *et al*. 2000; Jackson *et al*. 1994, 1997) is so preoccupied with an equilibrium perspective of reality, when confirmation of this worldview has not occurred in ecology (DeAngelis & Waterhouse 1987; Gunderson & Holling 2002)?

Simplification and mathematical tractability are important reasons why an equilibrium goal-orientation has persisted in economics even though near-equilibrium behaviour does not necessarily imply ecological sustainability, cultural survival or social fairness (Bishop 1993). Human welfare is clearly a multiple goal problem. For this reason, our theoretical evaluation of history should provide multiple reference points or models of reality. Therefore, in building a far-from-equilibrium interpretation of the history of human settlement on Rapa Nui there is need for competing or alternative explanations. This paper explores another perspective of reality from the reference point of resilience theory in ecology.

(See Gunderson & Holling (2002) for a comprehensive treatment of this subject.)

1.1. Resilience theory in ecology

The resilience paradigm in ecology has largely displaced the earlier equilibrium (Simberloff 1980) paradigm (DeAngelis & Waterhouse 1987). Some important characteristics of a far-from-equilibrium theory contrast with earlier equilibrium ecological organisation that implied the existence of: strong feedback regulation, principally through competitive effects, global stability, homogeneity, constancy and rigidity. A far-from-equilibrium theory of ecological organisation relaxes many of these assumptions.

First, it is now evident that processes of change in ecological systems are episodic and result from the interaction of variables that operate over different temporal and spatial scales; what Gunderson and Holling (2002) refer to as fast and slow variables.

Secondly, patchiness is a characteristic of ecological systems across all scales of organisation. Equilibrium theory assumed spatial uniformity. The existence of patchiness implies the existence of discontinuities between different levels of organisational scale. Therefore, movement from one level of organisational scale to another is likely to be mediated by non-linear processes (Gunderson & Holling 2002). Representing relationships of this kind is a challenge when attempting to model these systems.

Thirdly, the assumption of near-equilibrium behaviour in ecosystems was not necessarily wrong. Instead, it turns out to be an incomplete representation of reality since there are potentially many possible configurations for organising an ecological system (Strong 1986). Different organisational configurations are characterised by markedly different functional states and therefore different organising forces.

Fourthly, ecologists assumed that the variables that make up the stability-landscape did not change, largely due to the constancy of biotic ecological processes like competition and predation. Greater understanding of the central role of abiotic processes in the organisation of ecological systems necessitated revision of this assumption. It is now clear that the variables of the stability landscape constantly change in a way that both destroys and creates local attractors.

Fifthly, earlier equilibrium models tended to assume feedback-regulated mediated disturbance by a return to equilibrium. In a system far-from-equilibrium, the existence of multiple fixed points provides the pre-condition necessary for movement between differing locally attractive states (Gunderson & Holling 2002) mediated by disturbance events.

Finally, a far-from-equilibrium theory implies the importance of management practices that are: (i) flexible; (ii) reflexive (capable of learning by experimentation); (iii) aligned to the temporal and spatial scales at which critical ecosystem processes operate; and (iv) sensitive to the possible existence of multiple equilibrium states. A far-from-equilibrium theory of system organisation acknowledges the need for the system itself and those who manage it, to conserve at all costs *the ability* of the system to change. The ability to change includes maintaining capacity to buffer disturbance and adapt through innovation – thus maintaining a balance between *vulnerability and persistence* (Gunderson & Holling 2002). Given these characteristics of an ecological system far-from-equilibrium, what types of behaviour are implied?

1.2. Behaviour, far-from-equilibrium

Gunderson & Holling (2002) characterise the behaviour of an ecological far-from-equilibrium system using the *adaptive cycle*
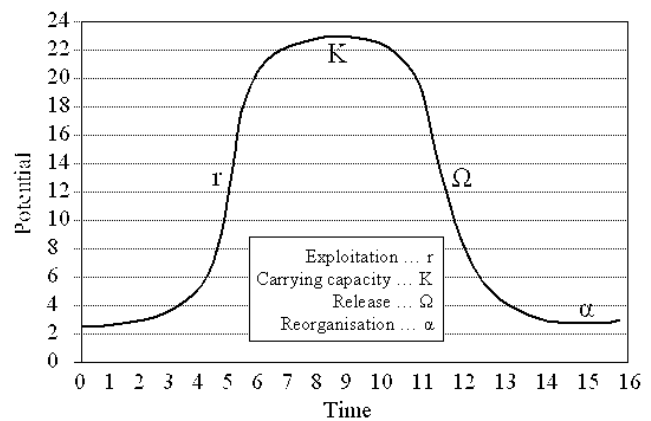

Figure 1 An adaptation of the density vague illustration of Strong 1986 showing the systems used to represent the developmental stages of an adaptive cycle.

metaphor (Fig. 2). This is a generalised approximation of a behavioural form that probably differs in specific cases. The adaptive cycle provides the possibility of movement between different states through disturbance mediated intervention. The conceptual derivation of the adaptive cycle can be obtained from Strong's (1986) illustration of density vague regulation by joining the start and end of the population density curve together and twisting it around into a figure-of-eight.

The theoretical justification for this reforming of Strong's model of density vague population regulation lies in the fact that it symbolises four characteristic stages of development in all ecological systems: exploitation (r); conservation (K); release (Ω); and re-organisation (α). These four developmental stages are identified in Figures 1 and 2 by the well-known terms of the Logistic equation (r and K) and two additional symbols (Ω and α) representing the release and re-organisation phases respectively.

When an ecological system reaches low density values after a major disturbance event, r-strategists (or pioneer species) seek to re-colonise the system. Pioneers tend to be better adapted to exploiting scarce resources (Fig. 1) and hence start the process of rebuilding the system back to a more complex conservation state that is by contrast to the exploitation phase, dominated by the presence of K-strategists. These species complete their life histories over long time periods; something that gives ecological systems in nature an appearance of stability (resistance to change).

Whilst seeking to remain at constant values in the conservation stage of an adaptive cycle, the system tends to become more rigid; something that signals a loss of resilience (i.e. the ability to change). Loss of resilience means vulnerability to disturbance events that can rapidly release the system from upper density values and return it to a developmental stage of low potential that then requires reorganisation and the work of r-strategists once again.

The classical notion of logistic behaviour derived from an equilibrium theory of ecological organisation was not necessarily wrong. Like Clementsian succession theory (Clements 1916), it was just incomplete. It portrayed the developmental pathway of an ecological population from pioneering stage to maturity while overlooking the fact that ecological systems are capable of being reset to initial conditions as a result of stochastic disturbance events like fire (Fig. 3).

The adaptive cycle is a behavioural model of a system far-from-equilibrium. The generalised form of this model provides a more complete behavioural characterisation of an ecological system when compared with earlier equilibrium theories of ecological organisation like the logistic equation or
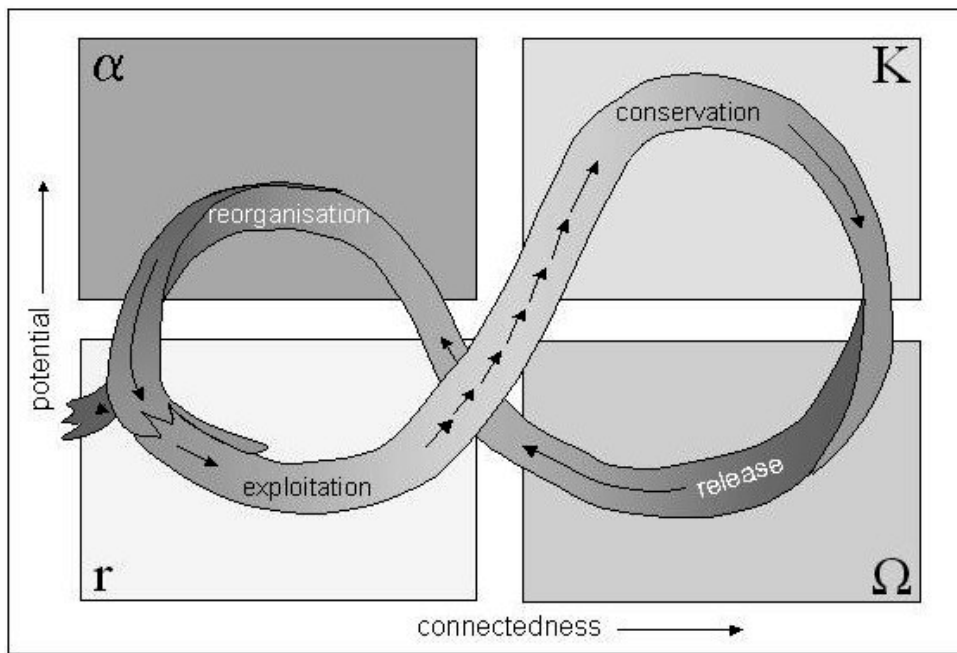
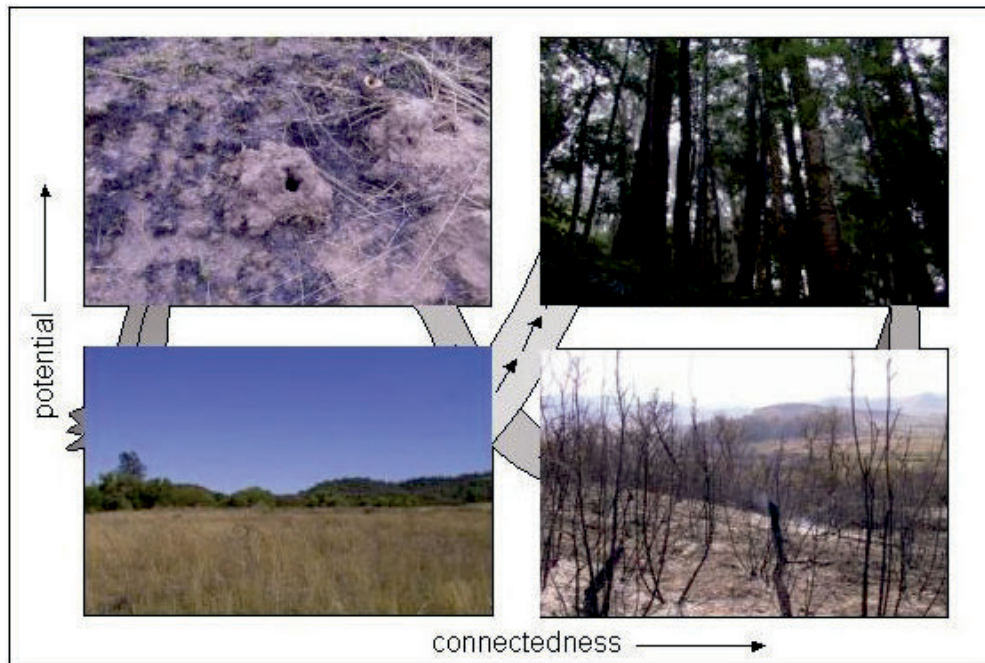**Figure 2** The stages of an adaptive cycle (based on Gunderson & Holling 2002).

Figure 3 Photographic representations of the four stages of an adaptive cycle starting with grassland in the exploitation stage leading to mature forest in the conservation stage. The mature forest is reduced to ashes in the release stage (a forest fire), while the first signs of reorganisation are seen in the sprouting of seeds (based on Gunderson & Holling 2002).

Clementsian theory of succession. This brings us to an important question. To what extent is the generalised behaviour of the adaptive model shared by socio-economic complex systems? In theory at least it is possible to model complex ecological, economic, cultural, social or institutional systems as adaptive cycles at different temporal and spatial scales.

1.3. Fast and slow variables

Central to the characterisation of adaptive cycles is the notion of fast and slow variables. Fast variables operate over relatively short time periods of hours to days, and usually occupy smaller areas of space. Slow variables operate over much larger time horizons (millennia) and can cover areas of large spatial

extent (even hundreds of square kilometres) (see Fig. 4). The ecological processes associated with these variables can be either reinforcing or destructive in their organising effect on an ecosystem. For example, as a form of intermediate disturbance (Connell & Keough 1984; Sousa 1979, 1984b) a forest fire (i.e. a fast variable) is essential in some ecosystems for maintaining high levels of biodiversity. However, a full forest fire (Sousa 1984a) is completely destructive over longer time horizons and areas of larger spatial extent (a slow variable).

Given the existence of complex ecological system of differing temporal and spatial character, it is unlikely that adaptive cycles exist independent of each other. Gunderson and Holling (2002) propose instead that: (i) *slow* (i.e. large spatial extent
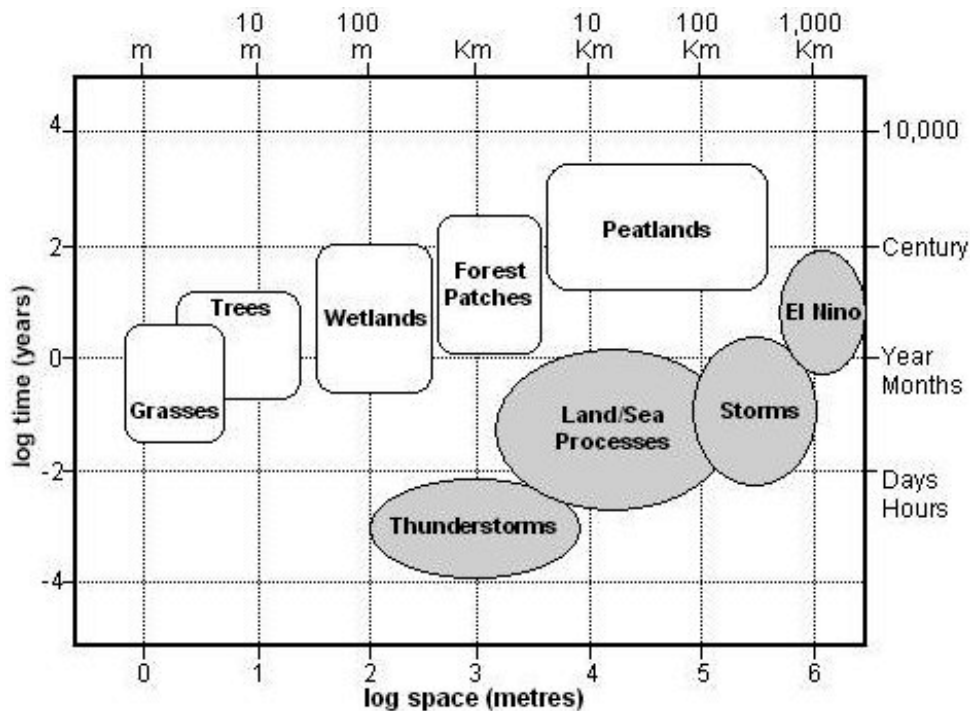
Figure 4 Fast and slow variables can be characterised by different temporal and spatial scales (based on Gunderson & Holling 2002).

and long time horizon) and (ii) *fast* (i.e. small spatial extent and short time horizon) variable co-exist in (iii) an inter-connected hierarchy of *fast and slow* variables (a Panarchy). This system of classification provides enormous scope for modelling complex systems far-from-equilibrium as defined by the human observer.

1.4. A Panarchy

Adaptive cycles can be positioned in a form of coupled spatial and temporal hierarchy in which the larger slower variables constrain or control the faster, smaller ones – a Panarchy. The couplings between levels are probably numerous, but because the various levels of this hierarchy operate at different time horizons, it is unlikely they are all in phase with each other. Slow variables can therefore become sensitive to changes in smaller, faster variables at the Ω and α transition points of the adaptive cycle. (The theoretical significance of the terms Ω and α is explained in relation to Figure 2.) The destruction and renewal (Ω) phases of each level of the hierarchy may therefore play an important role in the reorganisation of neighbouring adaptive cycles through the introduction of disturbance or variation into the system (Gunderson & Holling 2002).

1.5. Natural selection

Events involving the movement of a complex system from one local basin of attraction to another may provide a key to the problem of maintaining innovation and novelty. For example, the maturity of canopy trees in a forest produces a new basin of attraction for sub-canopy species to colonise in the newly formed forest soil below. Alternatively, the transformation of an adaptive system by fire results from the disturbance caused by a localised fast variable that spreads from one level to the next in a Panarchy. Through disturbance-mediated events of this kind, the adaptive cycle may give rise, in an ecological complex system, to the necessary pre-conditions for speciation at appropriate evolutionary time scales (Gunderson & Holling 2002).

1.6. Summary

Drawing from scientific epistemology, it has been noted that to retrospectively understand the process of human settlement on Rapa Nui, a hypothetico-deductive model of science should be employed. Competing hypotheses provide an opportunity to test comparatively both the predictive and explanation power of theory. This research project explores the predictive and explanatory power of a far-from-equilibrium theory of human settlement on Rapa Nui.

Recent theoretical developments in ecology have been surveyed to outline: (i) essential differences between equilibrium and far-from-equilibrium theories of ecological organisation; (ii) a conceptual derivation of the behaviour of a system far-from-equilibrium (i.e. an adaptive cycle); (iii) a classification of complex systems based on the notion of fast and slow variables; and (iv) options for coupling adaptive cycles to explore the role of highly complex, interconnected systems.

2. Working hypotheses

Based on the theory outlined in the previous section of this paper, a far-from-equilibrium interpretation of the human settlement history of Rapa Nui implies certain behaviours that can now be stated as a basis for our evaluation of published data.

2.1. Hypothesis 1 – Human population variability

We expect to find evidence that will lead us to conclude that human population change has been associated with multiple equilibrium states (a far-from-equilibrium interpretation) that are only locally stable, rather than staying in close proximity to a single equilibrium point (an equilibrium interpretation).

2.2. Hypothesis 2 – Changes in the stability landscape

Secondly, we expect to find evidence that human population change can be related to: (i) changes in the variables that constitute the local stability landscape; and (ii) adaptive strategies developed to cope with changing conditions. This
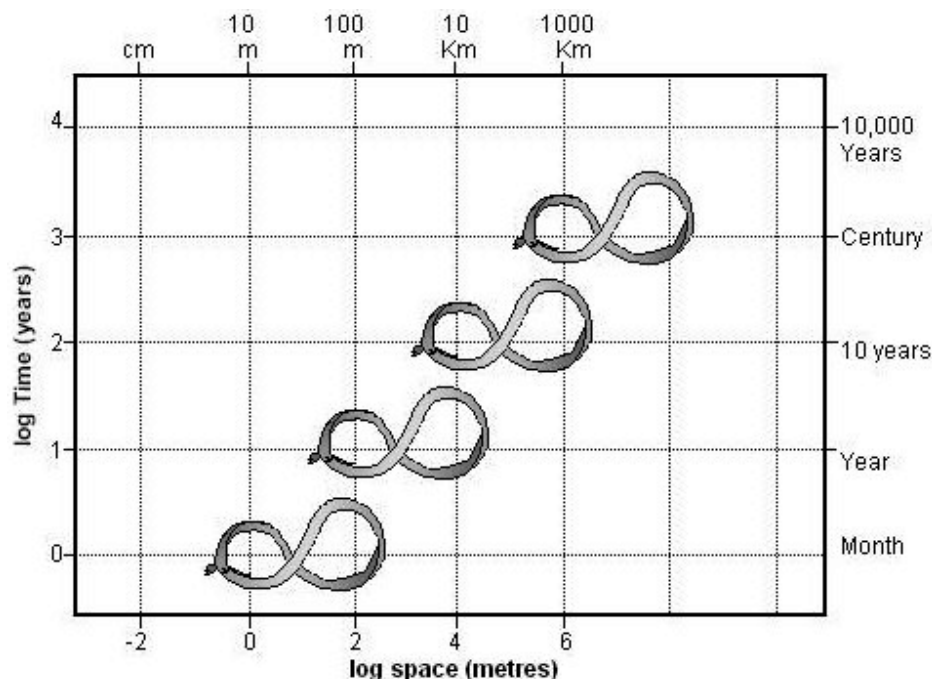
Figure 5 A Panarchy consisting of fast to slow variables coupled together across different temporal and spatial scales (based on Gunderson & Holling 2002).

far-from-equilibrium proposition may be contrasted with an equilibrium proposition that implies constancy in the variables of stability landscape and modes of human social organisation.

3. Methodology

A stepwise outline of our hypothetico-deductive research method is given in Figure 6. First, we plan our research method. This step includes consideration of the state of current knowledge to identify the starting point for either: (i) developing wild conjectures in the absence of existing theory or (ii) positioning our thinking amid existing theories. The former implies an inductive approach, the latter a deductive approach. The research plan also involves a statement of refutation criteria *a priori*. Choice of refutation criteria must be influenced by the current state of available data and to what extent the quality of these data can be used to support a conceptual, heuristic or theoretical (i.e. mathematical) modelling approach. However, we are also concerned with identifying competing theories to provide a basis for comparatively testing the explanatory power of theory.

The methodological basis for the first test is goodness-of-fit. It is difficult to specify refutation criteria precisely for goodness-of-fit in this case because of the inherent uncertainties associated with the historical data we are using. Therefore, we choose to assess goodness-of-fit heuristically. The second test involves a search for explanatory power related to the question "does a far-from-equilibrium model of human settlement help us to give logical explanation to the types of behaviour we see associated with the various lines of existing data used in this study". The refutation criteria associated with a test of this kind include: explanatory power, conflict with background theory, internal consistency, and parsimony.

Figure 6 shows the emergence from the research plan of two competing hypotheses that need to be reformulated into qualitative or quantitative models (referred to as conceptual models in Figure 6) relevant to the type/quality of available field data. For example, with access to very accurate time series data, experimental mathematical modelling could be undertaken.

Given the uncertainties of the historical data available for use in this research project, we chose to stay with conceptual models and tests of predictive power based around heuristic evaluation of model behaviour.

Before comparing the field and model data, it is necessary to collect and organise published data and bring these together into a comparative format. The way we planned to compare field data with our far-from-equilibrium conceptual model of human population change was to bring all these data together into a single comparative table as a test of consistency (i.e. do all the parts fit together?). Based on our refutation criteria, we then compare the field data with the conceptual models that represent the competing hypotheses. This leads us either to accept or to reject our working hypotheses. There is then need for a dialogue between the working hypotheses and base theory that may correct certain aspects of the theory or result in the reformulation of our initial hypotheses. This research methodology is intended as a starting point for developing new theory that will lead to new hypotheses and future research projects.

4. Results

This section of the paper outlines the results of the 'compare' stage of our research method as shown in Figure 6. Each line of published data is considered separately. Where appropriate, key assumptions associated with the use of the various published data sets are outlined.

4.1. Forest fossil pollen data

One of the important lines of evidence used to explore the behavioural predictions of a far-from-equilibrium hypothesis are data that record historic changes in forest and shrub vegetation of Rapa Nui. It is assumed that human settlement activity drew on this resource and that the nature, timing and extent of this resource use are recorded in the fossil pollen record. In evaluating these data, we are especially interested in identifying periods of forest decline *and recovery* (Fig. 7). Behaviour of this kind in the forest vegetation concurs with the
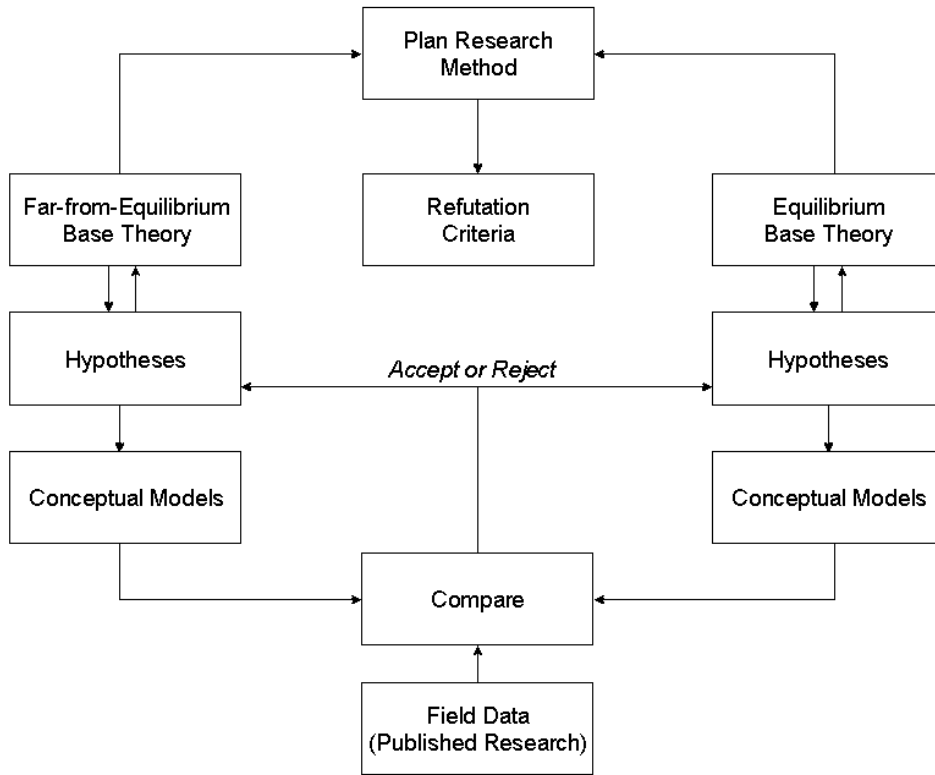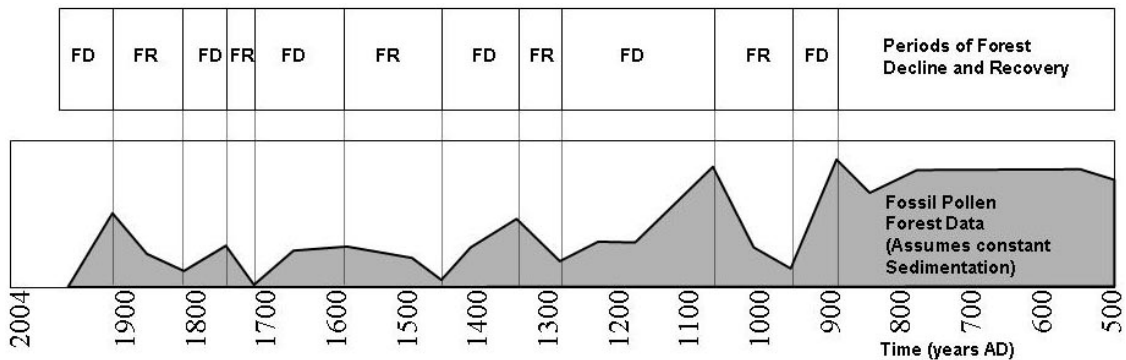
Figure 6   Research methodology.

Figure 7   A representation of fossil pollen data (from Butler & Flenley 2001) showing the identification of periods of forest decline (FD) and recovery (FR).

predictions of hypothesis one in the following way. Periods of decline in the forest vegetation are likely to result from one of three possible causes: (i) human harvest of the vegetation, (ii) abiotic or (iii) biotic drivers of forest vegetation change. The main concern in this paper is item (i). Future modelling research may help to test for the likelihood of items (ii) and (iii). It is unlikely that periods of recovery in the forest vegetation were driven by anything other than ecological causes and the relative absence of human consumption. Therefore, can it be concluded from this line of reasoning that a recovery period in the forest vegetation implies a period of human population decline? Correlation is not a proof of causation. However, it is a starting point for exploring hypothesis (i). Before progressing further with this line of thought, it is important to assess the quality of the forest fossil pollen data being used to develop this line of inquiry.

Unfortunately, attempts to radiocarbon date the core from which the data shown in Figure 7 came have produced anomalous results and the reasons for this are not entirely clear. A situation of this kind would normally lead us to seriously question the value of such data, were it not for the fact that it is possible to test the data quality through the use of an independent, replicate dataset. General consistency of results between the two fossil pollen datasets strengthens the likelihood that these data provide an important line of evidence about the nature, timing and extent of forest resource use.

4.2.   Evaluating forest fossil pollen data
The forest fossil pollen data shown in Figure 7 were generated from a core of floating mat and lake sediment samples taken from near the middle of the crater-lake, Rano Kau (Core KAO 2). The total length of this core is 21 m. However, the section of the core yielding the data shown in Figure 7 comes from the upper 3 m, which is a floating reed mat. A water body of approximately 8 m separates the bottom of this floating reed mat from the sediments at the bottom of the lake (Butler & Flenley 2001).

Organic matter from the base of the floating reed mat core has been radiocarbon dated at 1120 ± 110 years BP (approx. AD 830). Other dates obtained above this level are highly anomalous. It was initially thought that the anomaly might

have resulted from the release of ancient volcanic CO_2 within the crater (Butler *et al.* 2004), but radiocarbon dating of surface vegetation did not support this. There are three potential problems that follow from the anomalous dates. First, we are left to wonder if the variation in the fossil pollen signal indicates constancy of depositional processes or physical disturbance of the floating mat. Secondly, in the absence of consistent radiocarbon dates we have no way of dating the floating mat core. Thirdly, uncertainty in relation to the fossil pollen signal previously led us to question its role in informing the development of theory on the timing, nature and extent of human settlement (Cole & Flenley 2005). However, one way of testing the consistency of the floating mat data is to employ the use of an independent replicate (Walker 1990).

Replication of samples from two different cores tests for the existence of between site differences in the fossil pollen data. Once pollen diagrams have been produced, between-site comparisons can be made heuristically or by the use of multi-variate statistical tools such as cluster analysis. Heuristic evaluation is quite a valid approach, given that statistically speaking, we expect there to be variation in fossil pollen counts for a given taxon related to normal sample collection, processing and count variation. What we are really interested in is the co-occurrence between the two cores of a recognisable trend or signature in the fossil pollen record.

The core taken from the middle of the crater-lake, Rano Kau (Core KAO 2), provides an option for site replication. It is a well known fact that pollen deposition where a floating mat is developing will produce a fossil pollen signal more or less identical to that deposited in the lake sediments below (Tauber 1958). This is assuming that deposition rates for the floating mat and lake sediments are the same; otherwise differences in sedimentation rates would tend to obscure recognition of the fossil pollen trends produced by analysis of the two cores.

Had we thought of this earlier, the sampling intervals used in the analysis of the floating mat and lake sediment cores of Easter Island could have been standardised. This would have made comparison a relatively easy matter. Unfortunately, this was not done. The lake sediment was sampled at 10-cm intervals, while the floating mat was sampled at 10 and 20 cm intervals. Furthermore, sedimentation in the lake sediment appears to have been faster because there is a longer length (500 cm) of core and therefore more core samples *for the lake sediment data covering the fossil pollen history evident in the floating mat (275 cm)*. Therefore, to compare the two sets of core samples we need to address two problems: (i) differential sedimentation rates between the two cores; and (ii) the problem of differing sample intervals between the two cores.

The solution for addressing the second of these two problems was to seek to standardise the two datasets using a common mathematical interpolation algorithm supplied in the mathematical modelling software package called MatLab. However, standardising the sample intervals still did not solve the problem caused by a differential sedimentation rate and a general absence of reliable radiocarbon dates from the floating mat core. To overcome this first problem we rely on two things: (i) consistent basal radiocarbon dates; and (ii) temporal adjustment of the data where necessary.

First, the basal, bulk-sediment date (1120 ± 110 years BP, taken 2·85–2·95 m (NUTA – 3515)) from the floating mat core, concurs with the basal date that we interpolate ($992·5 \pm 110$ years BP) from two radiocarbon dates (11·35–11·45 m (NUTA – 3011) and 14·85–14·95 m (NUTA – 3013)) either side of the sample depth at which the fossil pollen signal in the lake sediment core begins to copy the fossil pollen signal in the floating mat core. These are comparable basal dates, but they give us no idea of how the sedimentation rate has altered in two different lengths of core. Therefore, second, we added extra data points based on existing values to parts of the data to make visual adjustment for obvious temporal misalignment of the data caused by variation in the sedimentation rate. The result is shown in Figure 8.

Overall, there exists a visible signature that may be recognised in both the floating mat and lake sediment datasets – accepting that the forest pollen percentage values tend to be higher in the lake sediment data. Figure 8 is interpreted by dividing the data into what are believed to be four periods of similarity. In interpreting these data, it is noted that the lake sediment core was longer and therefore has a greater number of sample points. This explains much of the variation in the data around the main trend line. A lack of similar variation in the floating mat core does not indicate a lack of similarity. In comparing the two data sets we are mainly concerned with the overall shape or signature of the two datasets rather than with the variation about this main trend.

Period 1 is between AD 700 and AD 1000, during which time both datasets show a strong background level of forest vegetation from AD 700 to approximately AD 940, at which time the forest pollen declines to low values.

Period 2 is between AD 1000 and AD 1300, during which time both datasets show an overall rise from low values and a decline back to low values. There is some dissimilarity between the two datasets related to the exact timing of the major peak in forest pollen and variation around that peak.

Period 3 is between AD 1300 and AD 1650, during which time the forest vegetation returns to higher values and then finally declines again to low values around AD 1650. Both datasets decline to intermediate values around AD 1450 to AD 1500. There is a noticeable difference in forest pollen concentration between the two sets of data.

Period 4 is from AD 1650 to AD 1950, during which time the forest vegetation returns to high values and declines.

Overall, this comparison indicates that the two datasets are independent representations of the same pollen depositional processes. Differences in the two sets of data can be explained by: (i) differential sedimentation rates for which it has not been possible to adjust the data in isolation from a series of consistent radiocarbon dates; (ii) the total number of core samples in the two datasets; and (iii) differences in fossil pollen values that would be expected in the course of a random sampling process.

The data shown in Figure 8 challenge the notion that forest decline on Rapa Nui was a progressive, long, slow decline from high to low values over some 1000 years following human settlement. An important question to be answered is why there were long periods of forest recovery. One possible explanation is that forest recovery was primarily a response to a decline in human consumption of available resources. This in turn suggests the existence of changes in the human population in a closed island ecosystem of this kind. This proposition is developed in the remainder of this paper.

In this initial analysis, only fossil pollen data from the floating reed mat is used as a source of forest data. All dates from this section of the core are ignored in this paper. Instead, it has been assumed, based on overall archaeological evidence (Flenley & Bahn 2003), that forest clearance would have begun about AD 900. To apply dates to the section of the core above this point, time has been mathematically interpolated with core sample depth, assuming a constant rate of sedimentation. In using these fossil pollen data (Fig. 8) it is assumed that a core sample taken from the middle section of the lake (as KAO 2 was) will give pollen assemblages that represent the forest vegetation on the island according to the well-established
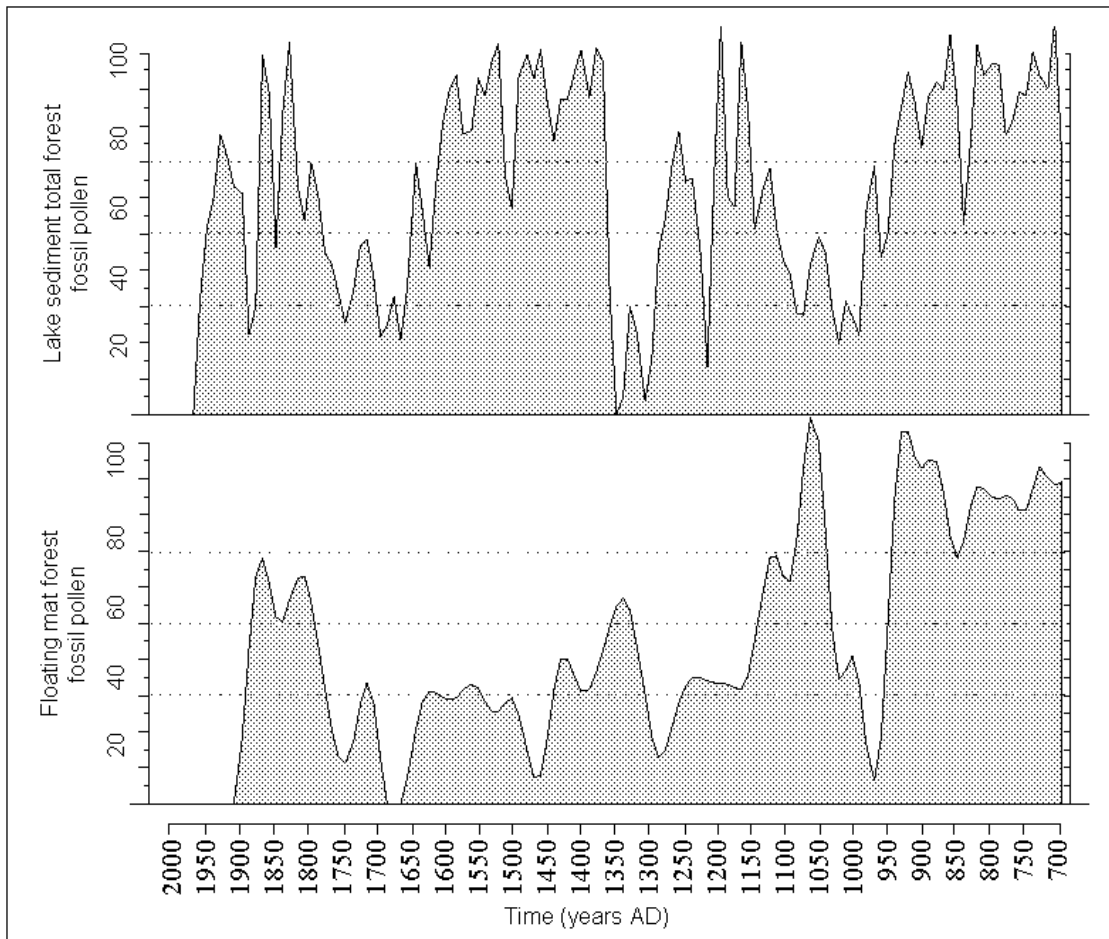
Figure 8   A between-site comparison of forest fossil pollen data.

pollen source and dispersal model for lake environments (Jacobson & Bradshaw 1980).

4.3. Building a competing conceptual model

As shown in Figure 6, these hypotheses of human settlement on Rapa Nui need to be translated into conceptual models. This work has already been done for the well-known equilibrium hypothesis (Fig. 10). There remains the need to formulate a competing far-from-equilibrium conceptual model. In a spatially homogenous, closed system, the behaviour of a human or animal population is bounded by physical laws of mass and energy conservation (Verhulst 1938). First, human populations cannot survive without material and energy resources. Secondly, the size of a population is constrained by the availability of resources. Therefore, the present authors conclude that if the forest resource base on Rapa Nui declines, the human population must to some extent also decline (often with a resource depletion time lag). Likewise, as the forest resource base recovers and increases this provides opportunity for human population increase, although maybe not instantaneously. It is argued that the behaviour of forest vegetation is a useful proxy indicator of human population behaviour. Based on these assumptions we attempt to build a time-series plot that provides a sense, at least conceptually, of what human population change over this time period might have looked like, assuming that the above assumptions hold true (Fig. 9).

This conceptual model of human population change is based on far-from-equilibrium theory. The rise of the human population to high density values equates to the exploitation-to-conservation phase of the adaptive cycle model shown in

Figure 2. The decline of the human population to low density values equates to the release phase of the adaptive cycle model shown in the same figure. The release proposed is mediated by resource scarcity caused by loss of the forest vegetation. Recovery from low-density values involves a period of re-organisation of the social system followed by an increase in human population numbers. Assuming that this interplay between resource use, scarcity and human population change is valid, this conceptual model of human population change indicates that human civilisation on Rapa Nui could have completed at least three adaptive cycles over the last 1500 years. This is represented in Figure 9 by placing adaptive cycle icon above the main stages, and it is suggested that each cycle is coupled to the one that follows it. That is, the collapse of the previous period of human population expansion provides the re-organisational start point for a new period of population expansion.

The conventional equilibrium interpretation of human population increase and decline on Rapa Nui is shown in Figure 10 and requires little interpretation. The human population expands to a theoretical island-carrying capacity (the solid line with dots) followed by population collapse resulting from the gradual depletion of resources (the dashed line). The differences in human population behaviour shown in Figures 9 and 10 raise an interesting research question. Given appropriate rates of growth, just how long would it take the human population on Rapa Nui to grow to a theoretical carrying capacity? This question could only be answered with the aid of an age cohort population growth model. However, this must remain a future research project; the present model is conceptual only.
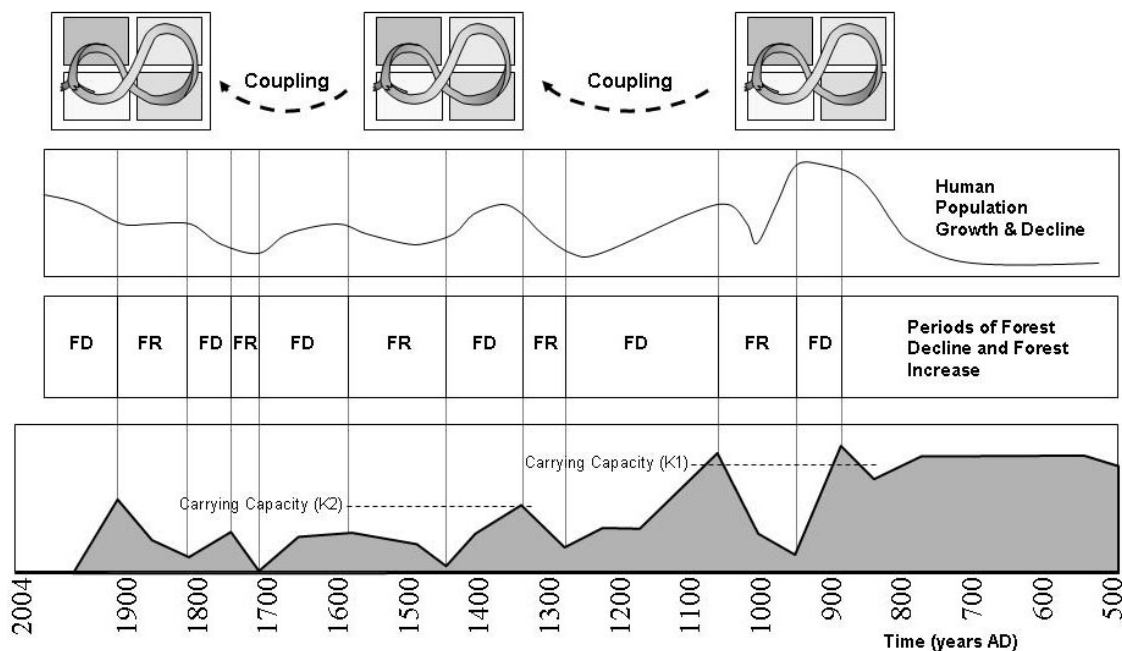
Figure 9 Inferring human population expansion and decline from forest fossil pollen data.
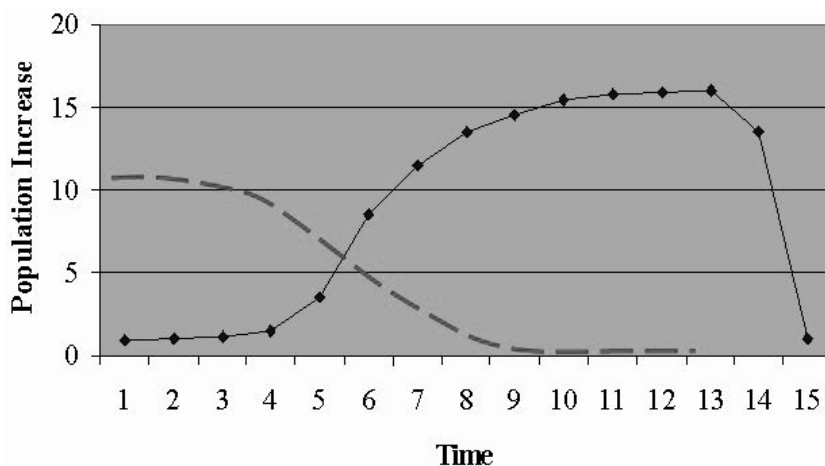

Figure 10 An equilibrium model of human population expansion and eventual collapse (the solid line with dots) resulting from resource depletion (the dashed line).

4.4. Stability landscape

In a complex system that is far-from-equilibrium, movement between various local attractive basins is mediated by disturbance events and change in the variables of the stability landscape that dictate the position and form of attractive basins. The former cause provides the trigger for movement between attractive basins. The latter cause could be thought of more as a measurement of the potential for movement (i.e. is there a neighbouring attractive basin at this point in time?) To portray a state change of this kind we use the concept of a stability-landscape that looks like a 3-dimensional table-like surface with mountains and hollows. The hollows are basins of local attraction around a fixed or equilibrium point. The mountains are quite the opposite – they represent regions of parameter space that repel rather than attract, and are therefore unstable. A stability landscape for Rapa Nui is portrayed in Figure 11.

The passage of a system across the surface of a stability landscape represents the passing of time at a constant rate. In an equilibrium view of reality, the complex array of variables that make up the stability landscape were thought to remain at constant values. However, it is now evident that this is not the case. The dynamic nature of these variables provides opportunities which, when combined with disturbances caused by other fast moving variables in the system, can catalyse 'release events' that mediate the movement of the system from one basin of attraction to another (Fig. 11). An attempt has been made to portray the stability landscape of Rapa Nui in Figure 11, bearing in mind that the static picture should look more like a time-lapse movie that represents the constant movement of mountains and basins and the arrival of sudden disturbance events.

The representation of the stability landscape of Rapa Nui portrays two important release events that mediate movement of the entire human/environment system between neighbouring basins of attraction. Figure 11 should be interpreted with the aid of Figure 9, which shows more clearly the likely timing of changes to the island's vegetation and human population. In Figure 7 it can be seen that the beginning of the settlement adaptive cycle of the human population, which began ca. AD 600, went through the characteristic collapse or release event about the year AD 900. This release event eventually moved the human/environment system into a new basin of attraction. As shown in the human population growth curve of
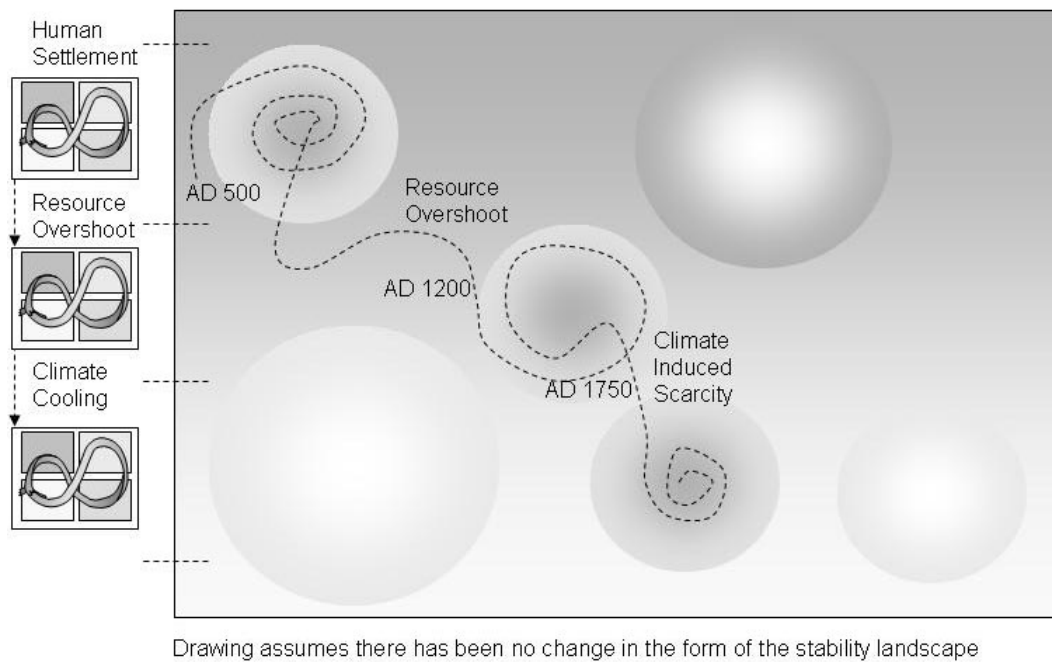
Figure 11 A two-dimensional static representation of the stability landscape of Rapa Nui.

Figure 9, this first release event was initially rapid, but may have been quickly followed by some resource recovery that temporarily increased human population numbers, but not enough to prevent a long-running population decline that is completed by ca. AD 1200.

At AD 1200 the human/environment system begins an orbit in a new adaptive cycle (also defined in Figure 11 by the second attractive basin). A second release event about the year AD 1600 mediates the movement of the human/environment system from this second adaptive cycle or basin of attraction to a third attraction basin or adaptive cycle that continues to the present time. Based on Figure 9, it is proposed that this new adaptive cycle was under way by about AD 1750.

4.5. Climate-induced scarcity

In addition to an interplay between the human population and forest resources, another crucial factor that may have helped drive the process of forest decline was the Little Ice Age cooling of climate in the southern parts of the Pacific (Nunn 2000). An important test of the present far-from-equilibrium conceptual model is the extent to which it provides an explanation of population change consistent with palaeo-temperature profiles. An attempt has been made to portray the Little Ice Age cooling trend by plotting the palaeotemperature profiles of Nunn (2000) and Palmer & Xiong (2004) on top of the forest pollen data of Butler & Flenley (2001) and, from this, the present interpolation of human population change shown in Figure 9.

Evidence of a behavioural correlation between the palaeo-temperature profile of Nunn (2000) and the forest pollen data of Butler & Flenley (2001) is represented in Figure 12. What this figure shows is that the general signature of palaeotem-perature peaks (W1, W2, W3) is replicated by a similar signature of forest vegetation peaks in the data of Butler and Flenley (2001), (W1′, W2′, W3′). After the corresponding peaks (W1–W1′) this pattern seems to breakdown and pre-sumably vegetation increase thereafter is controlled by a critical factor other than temperature warming. The response of the forest vegetation (W1′, W2′, W3′) lags behind corre-sponding peaks in palaeotemperature (W1, W2, W3) by

approximately 50 years. From an ecological perspective, this would be expected, although as mentioned earlier in this paper there is currently no complete control over time in the forest vegetation data. Further radiocarbon dating would improve confidence in this correlation, and by virtue of this the under-standing of the likelihood of a possible vegetation time lag.

Assuming that a correlation exists between mean climate adjustment and forest vegetation response, this would suggest that whilst human population decline provides opportunities for forest vegetation recovery, this process may be constrained or assisted by climate.

4.6. Shifting agriculture and forest clearance on the Poike Peninsula

A further line of palaeoecological evidence that can be drawn on for better understanding of the types of landscape changes occurring on Rapa Nui during the later phases of the Little Ice Age is provided by Mieth & Bork (2003) in their research on the Poike Peninsula. These authors show that a down-slope area of the eastern quarter of the Poike Peninsula underwent a first phase of dramatic ecosystem change following ca. AD 1280, including the clearance of *Paschalococos* Palm forest in preparation for ceremonial places, dwellings and agriculture (Mieth & Bork 2003; Grau 1997).

This period of dramatic landscape change appears to have concluded by AD 1400. In addition to this, the excavation of further archaeological sites indicates that a second phase of down-slope clearing and landscape modification probably lasted from ca. AD 1440 to 1650 (Fig. 13). The overlay of the Poike Peninsula data correlates with the cooling of climate portrayed in the palaeotemperature data of Nunn (2000). It may be that climate change required an adaptive response, especially given increasing scarcity of other resources that had previously been plentiful. It is interesting to note that phase (i) of forest clearance on the Poike peninsula correlates with our estimated human population expansion lasting from ca. AD 1200 to 1400. This period of population expansion may have been mediated by changing food provisioning technologies.
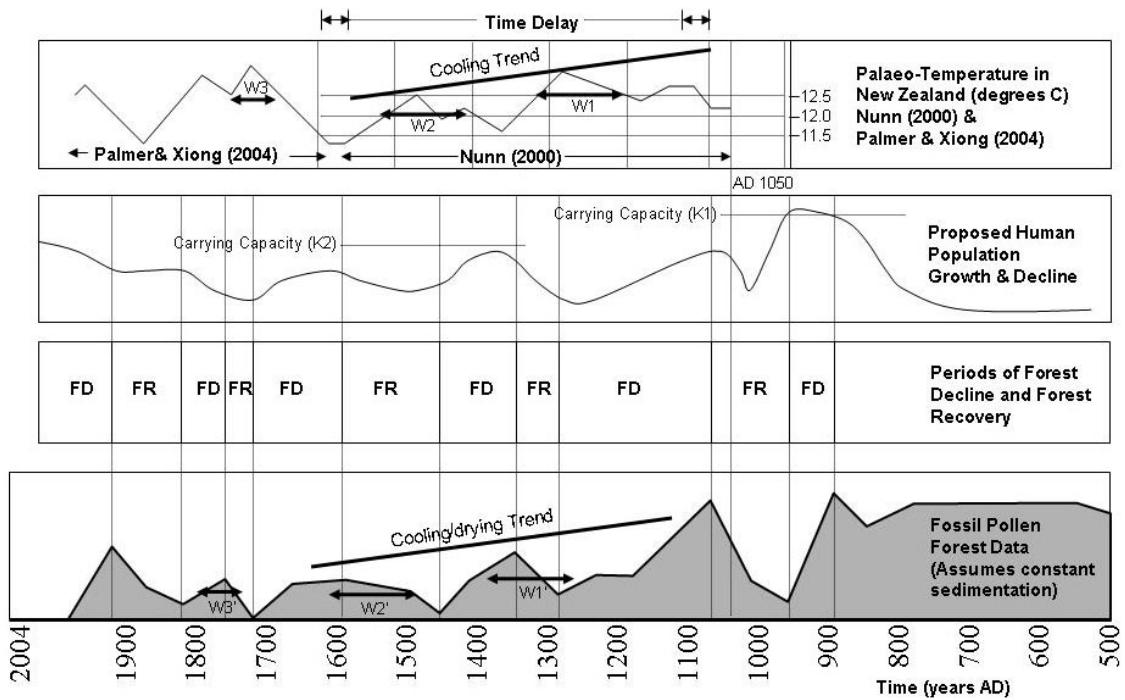
Figure 12 The palaeotemperature data of Nunn (2000) and Palmer & Xiong (2004) plotted against the present inferred plot of human population change based on forest pollen data of Butler & Flenley (2001).
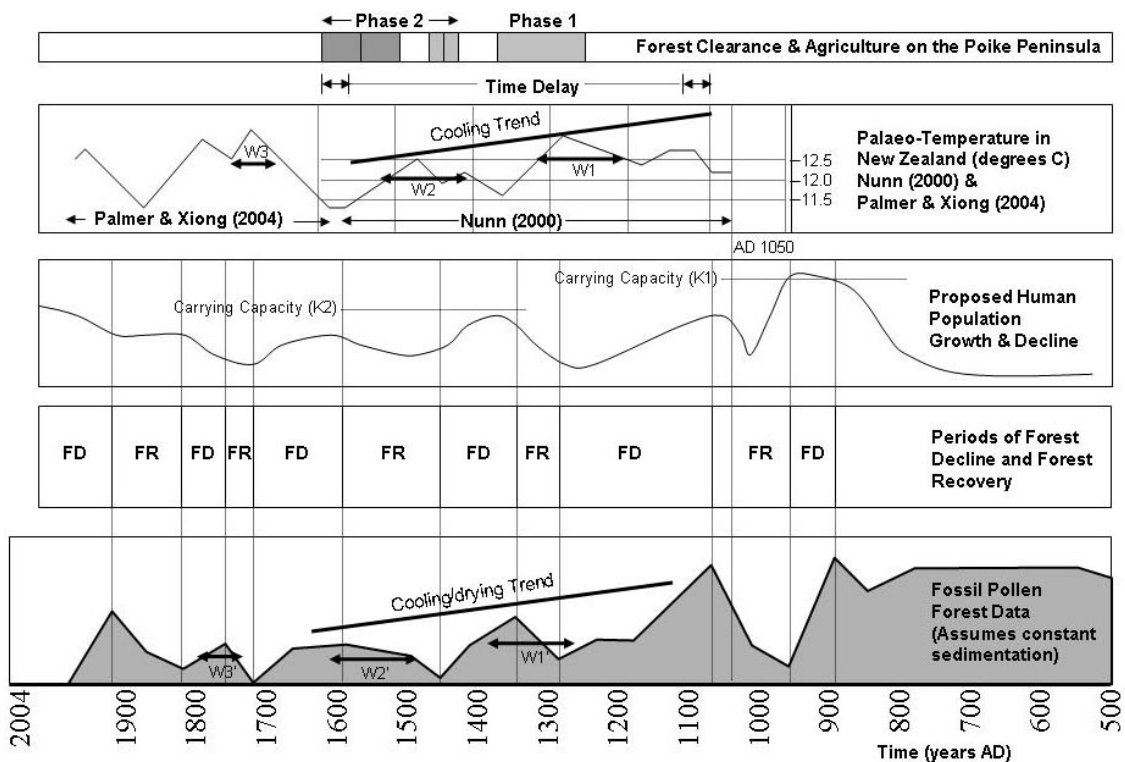

Figure 13 The portrayal of forest clearance and shifting agriculture on the Poike Peninsula in addition to the data portrayed in Figure 9.

4.7. Statue building and obsidian artefacts

Two final lines of published data on which we draw are provided in the empirical data of Van Tilburg (1994) and Stevenson *et al.* (2000). Statue building (Van Tilburg 1994) has played an important role in the cultural identity of the people of Rapa Nui, although the exact reasons for its rise and eventual decline have never been fully elucidated. According to the present far-from-equilibrium interpretation, a hiatus in statue building, based on radiocarbon dating of Van Tilburg

(Fig. 14), correlates with the peak of human population expansion over the period ca. AD 1150–1475 (Fig. 15). As shown in Figure 15, the peak of statue building as recorded in data of Van Tilburg lags in time behind the behaviour of rise and decline in the human population as inferred from the forest fossil pollen data of Butler & Flenley (2001). It is also interesting to note that the ascending limb of the statue building data of Van Tilburg covers a period of history characterised by cooling palaeotemperature and long-term
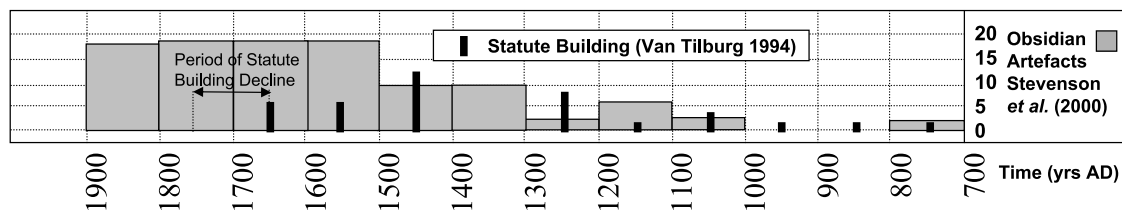
Figure 14 Plots of statue building data from Van Tilburg (1994) and Stevenson *et al.* (2000).

forest decline. By itself, it is difficult to see any connection between statue building and a far-from-equilibrium conceptual model of human population change. An incidental correlation exists between our human population curve based on forest vegetation decline and recovery and the peaks of the statue building data (labelled ('B') and ('A'), Fig. 15).

It is also interesting to note that a frequency plot of hydration-dated obsidian artefacts (Stevenson *et al.* 2000) correlates with the rise and eventual decline of the statue building activity (Fig. 14). This is significant because Stevenson *et al.* have shown that the main obsidian peak is composed largely of instruments of warfare (i.e. spearheads). It seems possible that statue building, the increase in obsidian artefacts, and the second human population increase and decline are all related. They may well have been associated with emerging social coping strategies during the period of history linked to what has been identified as the second adaptive cycle (Fig. 9).

4.8. Other lines of evidence

There are some other lines of research on which we can draw to test the consistency of a far-from-equilibrium theory. First, Flenley & Bahn (2003) provide estimates for likely periods of lowland and upland forest clearance. In Figure 15 it is interesting to note that these two periods of resource extraction and landscape modification correlate with two periods of human population expansion.

A further line of evidence concerns the decline of bird species (Fig. 15) as shown by Steadman (1995) between AD 1000 and AD 1300. During this period there was a second major decline in forest vegetation, according to the fossil pollen data of Butler and Flenley (2001). Of course, a period of species decline does not imply this was the only time bird species were harvested. Doubtless the early settlers on the Island found Rapa Nui's abundant supply of bird species an easy source of food.

Figure 15 also attempts to position the timing of forest clearance and shifting agriculture on the Poike peninsula between AD 1250 and 1650. It is interesting to note this intensification of agriculture correlates with the Little Ice Age cooling and drying trend, and may indicate that to a certain extent human population increase during this period was linked with agricultural intensification. A further line of research that would seem to support this conclusion draws attention to the existence of stone mulching in more climatically marginal areas of the La Pérouse coastal and lowland plains. According to obsidian hydration dating this form of agricultural practice lasted from AD 1250 to 1615 (Stevenson & Haoa 1997), a period of time that coincides with upland forest clearance (Flenley & Bahn 2003). After the clearance of the upland forest, the archaeological record shows a shift from the burning of wood to stem and rhizome vegetation (Orliac 2000). The timing of this shift coincides with the end of what has been identified as the second adaptive cycle.

Bird species decline indicates either prolonged or sudden and intensive harvesting of this resource exceeded its natural rate of replenishment. Whilst it is difficult to assess the exact cause of bird species decline in this case, it is interesting to note

that the decline occurred following what is hypothesised to be a time of human population decline, when other food and material resources were in short supply.

The birdman cult is another interesting aspect of the cultural history of Rapa Nui that may be linked to the adoption of a religious solution to the historic problem of resource depletion. The cult is associated with the most recent application of the adaptive cycle in the history of Rapa Nui in Figure 7. It is interesting to pose the question as to why this religious ceremony was not imported to the island with its first human settlers and then adapted to localised conditions as a mode of religious and cultural identity. Rather, the birdman cult emerges much later in the history of human settlement of the island. For this reason, it seems quite probable that it represents an adaptive strategy taken on by the island people to help them cope with an ever-changing environment and the social challenges this brought to the island.

Finally, we draw on the journal records of Roggeveen to pinpoint a time that demarcates the end of deforestation on the island (Von Saher 1990). In the scheme used to portray all this information, this milestone demarcates the transition between the 2nd and 3rd adaptive cycle of human civilisation we have attempted to portray in Figure 15.

5. Development of a summary results table

Table 1 is an attempt to portray changes in key variables over the history of human settlement on Rapa Nui. This history has been divided into three stages related to the three periods of human population expansion portrayed in Figure 9.

Figure 15 provides a useful summary of the various lines of evidence which have been drawn on to develop the framework shown in Table 1. The following narrative provides a more detailed summary and synthesis of this information and seeks to argue the case for a far-from-equilibrium interpretation of the history of this island based on the consistency of these various lines of evidence.

5.1. The first adaptive cycle of human population

As shown in Table 1, Stage 1 covers a period of time from approximately AD 600 to 1200. During this first exploitation period, those who settled the island would have learned to cope with a relatively stable climate and temperature regime that provided opportunity for population settlement and expansion. Furthermore, the settlers during this period were pioneers and opportunists who were not necessarily well adapted to managing available resources in accordance with their limited availability and the constraints of climate variability. Initially, they would have gathered resources from the coastal waters and lowland forests where they were readily available. As a result of the exploitation of these resources, the human population grew to a high-density conservation stage characterised by a general loss of resilience.

With the passing of time, these lowland resources would have become scarce and the human inhabitants would have
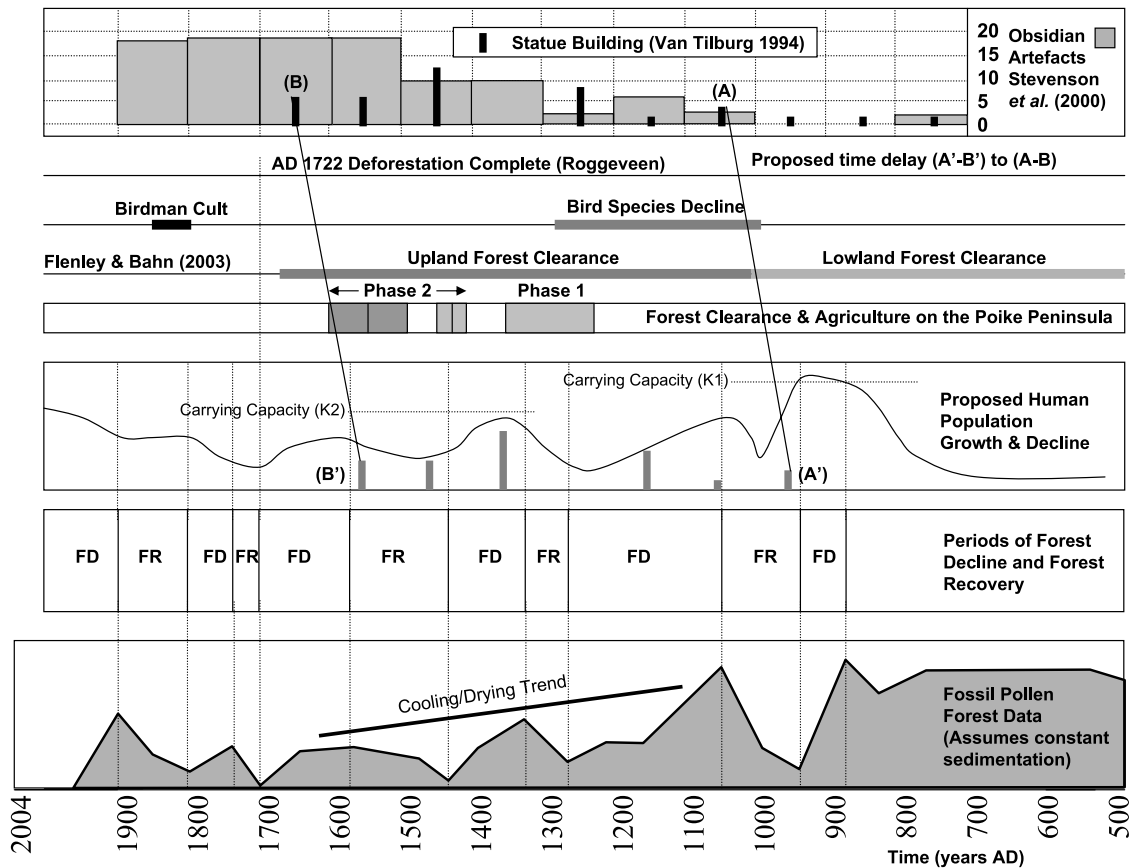
Figure 15 Other lines of evidence used to explore the far-from-equilibrium interpretation.

Table 1 Changes in possible slow and fast variables over the history of human civilisation on Rapa Nui that have changed the shape of the stability landscape

Variable (slow or fast)	Adaptive cycle of human population (Settlement)	Adaptive cycle of human population (Post-settlement)	Adaptive cycle of human population (Present day)
Stage	Stage 1	Stage 2	Stage 3
Period (Figure 7)	AD 900–1200	AD 1200–1700	AD 1700–Present
Lowland forest	Harvested	Harvest complete	Harvest complete
Upland forest	Harvest & Recovery	Harvest & recovery	Harvest complete
Temperature	Stable	Cooling & then warming trend	Stable
Climate	Stable	More variable	Stable
Human individuals	Initial state	Initial state plus learning and coping strategies	Initial state plus learning and coping strategies
Human social groups (e.g., clans)	Pioneers (intra-dependent)	Survivors (intra- and inter-dependent)	Post-Climate change (intra-dependent)
Release event	Resource scarcity	Climate variability	Yet to be determined
Bird Species	Abundant and then declining	Scarcity and local extinction	Scarcity and local extinction
Statue building	Starting	Highly active	Ending
Resource harvesting strategies	Lowland forest and coastal resources	Upland forest and shifting agriculture	Importing resources
Obsidian artefacts	Low	Medium	High

been forced to migrate further inland in search of alternative resources. Social groupings would have been intra-dependent during this period of time, reflecting the normal human behaviour associated with looking after those within the immediate and/or extended family. During this stage of development, statue building starts, while there is very little evidence of the existence of obsidian artefacts.

The limited understanding of what happened to the human population at this time suggests that the decline in availability of key resources resulted in population overshoot and resulting decline – a release event. Resource scarcity represents a critical change in the stability landscape. The human population was moved from this initial local equilibrium to a neighbouring basin of attraction.

For the present time it is not easy to speculate which fast variable was responsible for mediating the release event that moved the population from this initial pioneering basin of attraction to a new locally stable orbit. Human population decline could have been triggered by a number of causes associated with density-dependent regulation (famine, warfare (fighting for resources), epidemic, migration).

During the re-organisation period, it can be expected that the survivors of this initial release event would have had to re-organise their resources and skills in novel new ways that made it possible for them to cope with conditions and opportunities available for the growth and development of the human population as new resources became available.

5.2. The second adaptive cycle of human population

As shown in Table 1, Stage 2 covers the period from approximately AD 1200 to 1700. During this period the harvesting of available resources from the lowland forest was completed and we now see harvesting and recovery of the upland forest. The use of this resource base would have provided opportunity for population expansion during an initial exploitation or growth stage.

In contrast with earlier recovery of the upland vegetation, the process of recovery of the upland forest may well have been affected by a general cooling/drying of climate and an increase in local climatic variability associated with Little Ice Age conditions. Humans living on the island had to learn to cope with this increase in climate variability on the one hand and limited resources on the other. This could have led to the development of resource-gathering strategies that include forest clearance and shifting agriculture like that practised on the Poike peninsula, and stone mulching. It has been noted this period of agricultural intensification also correlates with the stone mulching hypotheses of Stevenson & Haoa (1998). Other strategies include differing forms of social organisation that may have been based on traditional methods of caring for those in the immediate social group as well as competing with those in other groups for available resources.

Competition for scarce resources may be reflected in the increased levels of obsidian artefacts of this period, largely warfare-related in nature. However, the height of statue building during this period also reflects a certain sense of optimism, given that this activity drew so heavily on resources, human and natural.

It is once again difficult to say exactly which fast moving variable was responsible for returning this period of human population expansion to lower values (the release event). What is evident from the fossil pollen and palaeotemperature data is that the availability of resources continued to decline in an environment characterised by cooling temperatures and increased climate variability (droughts). The release event may therefore have been characterised by a combination of factors including competition for diminishing resources, conflict and/or threshold events like climate-induced famine, epidemics or migration that mediated the release event that returned the population to low-density values. The human population now moved into a locally stable basin of attraction in which conditions were very different from those that met the very first settlers on the island.

5.3. The third adaptive cycle of human population

As shown in Table 1, Stage 3 covers a period of time from approximately AD 1700 to the present day. By this stage the clearing of lowland and upland forest was complete. A period of climate amelioration followed the cooling trend of the Little Ice Age. Human population density was lower, so social organisation was not characterised by conflict and competition for resources. However, because of the greatly changed resource base of the island, there was still a need for the ongoing development of learning and coping strategies, as evidenced by the emergence of the birdman cult and high levels of obsidian artefacts. Statue building was now in a decline that may have been related to limited resources, which apart from physical

resources like wood may have included necessary people power. There has been a shift in fuel use from forest timber to stem and rhizome vegetation.

This is the re-organised context in which the development of the human population must now occur during a third exploitation stage. During this human population expansion, the beginning of the age of exploration in Western civilisation began and linked the island community with the rest of the world, missionaries, trade and the conveniences of our modern world. This final application of the adaptive cycle is therefore incomplete.

6. Discussion

The main aim of this paper has been to develop an alternative hypothesis to a more standard equilibrium interpretation of the history of human settlement on Rapa Nui as portrayed in Figure 10. We test a far-from-equilibrium explanation of the history of human settlement on this island to see if it offers superior explanatory power, is consistent with other lines of published data, and does not conflict with background theory as given by Gunderson and Holling (2002).

6.1. Exploring an equilibrium interpretation of this history

A near-equilibrium interpretation of population behaviour can be identified by a number of key characteristics including: (i) a single equilibrium point; (ii) stability resulting from strong feedback regulation; (iii) constancy in the variable of the stability landscape; and (iv) human behavioural response to environmental constancy which lacks the development of coping and learning strategies. As Gunderson and Holling (2002) have suggested, an equilibrium interpretation of the behaviour of a complex system is not necessarily wrong, but it may be incomplete. Complex systems not only go through periods of growth and expansion, they also go through periods of collapse and re-organisation following severe disturbance events. Is an equilibrium interpretation consistent with published data? The present authors believe this is not the case for a number of reasons:

6.1.1. An absence of steady forest decline. First, if we are to assume an equilibrium interpretation of the behaviour of the human population on Rapa Nui, then we need to be able to demonstrate that upland and lowland forest vegetation density declined gradually as expected by a single, resource-limited human population collapse event. The fossil pollen evidence of Butler and Flenley (2001) suggests this was not the case (Figs 7–8). Therefore, it is very difficult to accept an equilibrium interpretation of resource use and human population behaviour on these grounds alone.

6.2.1. An absence of constancy in the stability landscape. Secondly, as shown in Table 1, it is highly likely that key variables that constitute the stability landscape of the Rapa Nui civilisation have continued to change and adjust during the history of human settlement on the island. For this reason, we can be sure that the attractive basins in the stability landscape have also changed their position and character. Once we accept this fact, it is not difficult to build a far-from-equilibrium model of human settlement. Over the very time horizon that a population grows to maximum density as allowed by the local carrying capacity, the variables that initially defined that carrying capacity have now changed so that population growth and expansion often occur at the cost of a loss of resilience. Changes in the stability landscape not only result in a loss of resilience for an existing, locally stable equilibrium, but they can also result in the emergence of new opportunities that did not formerly exist.

6.2.2. The existence of coping and learning behaviours. Thirdly, the rise and fall of the human population on Rapa Nui over the history of the last 1500 years also makes more evident the counterplay that exists between population decline and the emergence of possible learning and coping mechanisms, including: (i) stone mulching, (ii) agricultural intensification, (iii) moving from one depleted resource (e.g., birds) to an alternative; and (iv) the use of obsidian. Evidence of learning introduces another variable of change in the stability landscape that needs to be taken into consideration in our preferred choice of theory for interpreting the history of this island.

6.2.3. Not a stable equilibrium.   In the absence of knowledge of ecological disturbance, our palaeoecological records of forest decline show there was a rapid decline in forest vegetation. In this paper we have assumed that forest decline resulted in human population decline because there was no technological substitution for depleted resources. Possible variables that could have triggered the release event include: (i) competition for resources; (ii) emigration; (iii) epidemics; (iv) human learning and coping mechanisms that ere not rapid enough avert the coming crisis; and possibly (v) warfare.

In summary, this analysis has shown that an equilibrium hypothesis struggles to explain and predict the following aspects of human settlement on Rapa Nui: (i) expansion and decline of forest vegetation; (ii) changes in the stability landscape; (iii) the existence of coping and learning strategies; and (iv) rapid forest decline. Based on this somewhat limited initial evaluation of published data and theory, the present authors believe that a far-from-equilibrium theory offers superior explanatory and predictive power. Future palaeoecological research and mathematical modelling will provide opportunity to further test and explore these conclusions.

7. Conclusions

In this paper, an attempt has been made to develop an alternative to the standard equilibrium hypothesis that has been used to interpret the history of human settlement on Rapa Nui. This far-from-equilibrium hypothesis suggests there has been not one, but at least three periods of human population expansion on the island that can be related to changes in the variables that constitute the stability landscape for this island system. This research suggests that the human population has moved between at least three different locally stable basins of attraction mediated by disturbance events. The main aim in developing this interpretation has been to build an over-arching framework. We believe we have been successful in providing the narrative, but more research is required to validate individual parts of this story. This includes mathematical modelling that would help to provide an empirical basis on which to explore this interpretation in greater detail.

Finally, much of our thinking about the problem of sustaining human civilisation has been based on the simplistic assumptions of equilibrium theory. A far-from-equilibrium interpretation of the history of human settlement and expansion on Rapa Nui draws our attention to a sobering reality. A steady-state future for human civilisation may not be as easy as we would like to think.

8. References

Bishop, R. C. 1993. Economic efficiency, sustainability and biodiversity. *AMBIO* **22**, 69–73.

Brander, J. A. & Taylor, M. S. 1998. The simple economics of Easter Island: A Ricardo-Malthus model of renewable resource use. *The American Economic Review* **88**(1), 121–38.

Butler, K., Prior, C. A., & Flenley, J. R. 2004. Anomalous radiocarbon dates from Easter Island. *Radiocarbon* **46**(1), 395–405.

Butler, K. & Flenley, J. 2001. Further pollen evidence from Easter Island. *In* Stevenson, C. M., Lee, G. & Morin, F. J. (eds) *Fifth International Conference on Easter Island and the Pacific*, 79–86. Los Osos, California: Bearsville Press.

Byrns, R. T. & Stone, G. W. 1992. *Economics*, 5th edn. New York: Harper Collins.

Chesson, P. L. & Case, T. L. 1986. Overview: Non-equilibrium community theories: Chance, variability, history and coexistence. *In* Diamond, J. & Case, T. J. (eds) *Community ecology*, 229–39. New York: Harper and Row Publishers.

Clements, F. E. 1916. *Plant succession: An analysis of the development of vegetation*. Washington: Carnegie Institute.

Cole, A. O. & Flenley, J. R. 2005. Human settlement of Easter Island: a far-from-equilibrium model. *In* Stevenson, C. M., Ramirez, J. M., Morin, F. J. & Barbacci, N. (eds) *Proceedings of the Conference on Easter Island and the Pacific*, Vina del Mar, Chile, September 2004. Los Osos, California: Easter Island Foundation.

Connell, J. H. & Keough, M. J. 1984. Disturbance and patch dynamics of subtidal marine animals on hard substrata. *In* Pickett, S. T. A. & White, P. S. (eds) *Natural disturbance: The patch dynamics perspective*, 125–47. New York: Academic Press.

DeAngelis, D. L. & Waterhouse, J. C. 1987. Equilibrium and non-equilibrium concepts in ecological models. *Ecological Monographs* **57**, 1–21.

Edward-Jones, G., Davies, B., & Hussain, S. 2000. *Ecological economics An introduction*. Oxford: Blackwell Science.

Erickson, J. D. & Gowdy, J. M. 2000. A tale of two Pacific Island cultures. *Land Economics* **76**(3), 345–54.

Flenley, J. & Bahn, P. 2003. *The enigmas of Easter Island*. New York: Oxford University Press.

Grau, J. 1997. *The Jubaea palm: Key in the transportation of Maoi on Easter Island*. University of New Mexico, Albuquerque: Easter Island Foundation.

Gunderson, L. H. & Holling, C. S. 2002. *Panarchy: Understanding transformations in systems of humans and nature*. Washington DC: Island Press.

Jackson, J., McIver, R., McConnell, C., & Brue, S. 1994. *Micro economics*, 4th edn, 670–80. Sydney: McGraw-Hill.

Jackson, J., McIver, R., McConnell, C., & Brue, S. 1997. *Economics*, 4th edn. Sydney: McGraw-Hill.

Jacobson, G. L. & Bradshaw, R. H. W. 1980. The selection of sites for palaeovegetational studies. *Quaternary Research* **16**, 80–96.

Loehle, C. 1983. Evaluation of theories and calculation tools in ecology. *Ecological Modelling* **19**, 239–47.

Mahon, I. 1998. Easter Island: The economics of population dynamics and sustainable development in Pacific context. *In* Stevenson, C. M., Lee, G. and Marin, F. J. (eds) *Easter Island in Pacific Context: South Seas Symposium*, 113–19. Proceedings of the 4th International Conference on Easter Island and East Polynesia, University of New Mexico, Alberquerque, 5–10th August 1997. Los Osos, California: Easter Island Foundation.

Mieth, A. & Bork, H. R. 2003. Diminution and degradation of environmental resources by prehistoric land use on Poike Peninsula, Easter Island (Rapa Nui). *Rapa Nui Journal* **17**(1), 34–41.

Nunn, P. D. 2000. Environmental catastrophe in the Pacific Islands around A.D. 1300. *Geoarchaeology: an International Journal* **15**(7), 715–40.

Orliac, C. 2000. The woody vegetation of Easter Island between the early 14th and the mid-17th Centuries AD. *In* Stevenson, C. M. & Ayres, W. S. (eds) *Easter Island archaeology and research on early Rapanui culture*, 211–20. Los Osos, California: Easter Island Foundation.

Palmer, J. & Xiong, L. 2004. New Zealand climate over the last 500 years reconstructed from *Libocedrus bidwillii* Hook. f. tree ring chronologies. *The Holocene* **14**(2), 282–9.

Platt, J. R. 1964. Strong inference. *Science* **146**, 347–53.

Popper, K. 1963. Conjectures and refutations: the growth of scientific knowledge. (1st Edition). London: Routledge and Kegan Paul.

Quinn, J. F. & Dunham, A. E. 1983. On hypothesis testing in ecology and evolution. *The American Naturalist* **122**, 602–17.

Rafael, R. & Decker, C. S. 2000. Easter Island: Historical anecdote or warning for the future? *Ecological Economics* **35**, 271–87.

Simberloff, D. 1980. A succession of paradigms in ecology: Essentialism to materialism and probabilism. *Synthese* **43**, 3–39.

Sousa, W. P. 1979. Disturbance in marine intertidal boulder fields: The Non-equilibrium maintenance of species diversity. *Ecology* **60**, 1225–39.

Sousa, W. P. 1984a. The role of disturbance in natural communities. *Annual Review of Ecology and Systematics* **15**, 353–91.

Sousa, W. P. 1984b. Disturbance and patch dynamics on rocky intertidal shores. *In* Pickett, S. T. A. & White, P. S. (eds) *Natural disturbance: The patch dynamics perspective*, 101–24. New York: Academic Press.

Steadman, D. W. 1995. Prehistoric extinctions of Pacific Island birds: Biodiversity meets zooarchaeology. *Science* **267**, 1131–2.

Stevenson, C. M., Ramirez, J. M., Haoa, S., & Allen, T. 2000. Archaeological investigations at 'Anakena Beach and other near-coastal locations'. *In* Stevenson, C. M. & Ayres, W. S. (eds) *Easter Island archaeology research on early Rapanui culture*, 147–72. Los Osos, California: Bearsville Press.

Stevenson, C. M. & Haoa, S. 1998. Prehistoric gardening systems and agricultural intensification in the La Pérouse area of Easter Island. *In* Stevenson, C. M., Lee, G. & Marin, F. J. (eds) *Easter Island in Pacific Context: South Seas Symposium*, 205–13. Proceedings of the 4th International Conference on Easter Island and East Polynesia, University of New Mexico, Alberquerque, 5–10th August 1997. Los Osos, California: Easter Island Foundation.

Strong, D. R. 1986. Density-vagueness: abiding the variance in the demography of real populations. *In* Case. T. J. and Diamond, J. (eds) *Community ecology*, 257–68. New York: Harper and Row.

Tauber, H. 1958. Difficulties in the application of C-14 results in archaeology. *Archaeologia* **24**, 59–69.

Van Tilburg, J. A. 1994. *Easter Island: archaeology, ecology and culture*. Washington DC: Smithsonian Institution Press.

Verhulst, P. F. 1938. Notice sur la loi que la population suit dans son accroissement. *Correspondence in Mathematics and Physics* **10**, 113–21.

Von Saher, H. 1990. Some details of the journal of Jacob Roggeveen. *Rapa Nui Journal* **4**(3), 33–5.

Walker, D. 1990. Purpose and method in Quaternary palynology. *Review of Palaeobotany and Palynology* **64**, 13–27.